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ABSTRACT

Citizen science broadly describes citizen involvement in science. Citizen science has gained significant momentum in recent years, brought about by widespread availability of smartphones and other Internet and communications technologies (ICT) used for collecting and sharing data. Not only are more projects being launched and more members of the public participating, but more human–computer interaction (HCI) researchers are focusing on the design, development, and use of these tools. Together, citizen science and HCI researchers can leverage each other's skills to speed up science, accelerate learning, and amplify society's well-being globally as well as locally. The focus of this article is on HCI and biodiversity citizen science as seen primarily through the lens of research in the author's laboratory. The article is framed around five topics: community, data, technology, design, and a call to save all species, including ourselves. The article ends with a research agenda that focuses on these areas and identifies productive ways for HCI specialists, science researchers, and citizens to collaborate. In a nutshell, while species are disappearing at an alarming rate, citizen scientists who document species' distributions help to support conservation and educate the public. HCI researchers can empower citizen scientists to dramatically increase what they do and how they do it.

1. Introduction

"We live in times of great changes on Earth. . . . while previous shifts from one geological epoch to another were caused by events beyond human control, the dramatic results of our emission of carbon into the atmosphere over the past century have moved many scientists to declare the dawn of a new era: the *Anthropocene*, or the *Age of Man*" (Vince, 2014, back cover). According to Harvard biologist Edward O. Wilson and others, the anthropocene is the first geological period that humans have actively created (Crutzen, 2002; Kolbert, 2014; Wilson, 2016).

The destructive effects of our impact on the planet are evident every day: rubbish dumps of non-biodegradable polystyrene, plastic bottles, and old cars are a blight on the landscape; mountaintop mining scars and changes the contours of the land; toxic runoff from farming and manufacturing kills life in lakes, rivers, and the seas; human rubbish forms huge floating islands in the oceans; housing developments, roads, and other forms of human infrastructure destroy ecosystems and habitats for wildlife; and global warming bleaches vast areas of coral and changes ocean habitats. Polar ice caps are melting; abnormal variations in seasonal changes are disrupting ecosystems and forcing organisms to migrate to new environments; and wind turbines kill migrating birds. We humans are carrying out mass slaughter of wildlife, trafficking in animal parts, and destroying virgin forests.

We have trodden with heavy footsteps on our planet, taking what we need to feed, house, protect, and indulge our growing populations. Biologists point out that the average rate of vertebrate species loss over the last century is up to 100 times higher than previous rates of extinction (Ceballos et al., 2015). Our large brains and versatile thumbs have enabled us to create artifacts that magnify our impact with heavy lifting gear and explosives, orchestrated by computer technology. Yet these same capabilities can create new ways to use raw resources wisely, recycle more, and find alternative pathways to nurture and protect our own species without devastating the planet and forcing other species into extinction (Kolbert, 2014; Vince, 2014; Wilson, 2016).

Perhaps we are beginning on that course. The Paris Agreement reached during the 2015 UN Climate Change Conference and signed by nearly 200 countries represents global consensus on the policy goals of keeping global temperature increases at "well below" 2.0 C/3.6 F above pre-industrial temperatures and capping the greenhouse gases caused by human activity to the level that can be naturally absorbed by trees, soil, and oceans, starting between 2050 and 2100. As important, the Paris Agreement makes each country accountable for reviewing progress every 5 years and calls on wealthier countries to provide financial assistance to support poorer ones in adapting to climate change and switching to renewable energy. Citizen science involves members of the public contributing to scientific research (Bonney et al., 2009; Cooper, 2013; Dickinson & Bonney, 2012; Silverton, 2009). Citizen science has a role in monitoring climate change and biodiversity.

Human–computer interaction (HCI) specialists can help by contributing to the development of low-energy technology that fosters sustainability in developing countries (e.g.,

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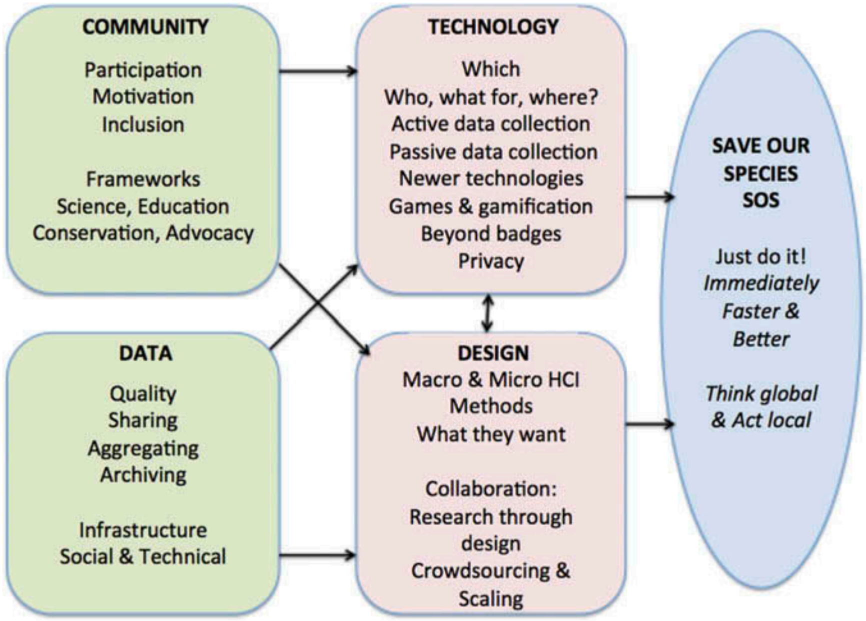


Figure 1. Challenges for citizen science and human–computer interaction (HCI).

Grunfeld & Houghton, 2013; Shrinivasan et al., 2013). Deep understanding of local conditions and cultures is a baseline requirement for successful design (Gui & Nardi, 2015). Of course, it is not just developing countries that can benefit from the ingenuity of HCI researchers. There are water shortages throughout the world, including extreme droughts in California and the southern United States. Devices that help to remind us not to run water continuously while we clean our teeth or indulge in very long showers encourage behavior change (Froehlich, Findlater, & Landay, 2010).

In addition to supporting the development of sustainability technologies, HCI researchers can also contribute to educational efforts that serve the environmental cause through citizen science. When these projects are online, they may also be referred to as "citizen cyberscience" (Haklay, 2013a; Jennett et al., 2016) Developing free education via massive open online courses (MOOCs) with interaction that supports different cultures and languages and that is accessible via low-cost mobile devices is another opportunity for HCI specialists. Tying in education with citizen science and vice versa can be promising and is already done both formally and informally through bioblitzes, concentrated efforts to document all living things in a specific area over a short period of time. Involvement of citizens in collecting scientific data is at an all-time high and poised to continue as technologists strive to develop even more powerful technology and infrastructure that will eventually touch even the remotest parts of the world. The time is right for HCI specialists and citizen scientists to leverage each other's skills for positive change.

The focus of this article is biodiversity citizen science. It emphasizes the need for citizens, scientists, and HCI specialists to work collaboratively and presents a research agenda to stimulate action across both fields. Specifically, it explores how HCI can help support the development of richly interactive citizen science communities by motivating participation, paying attention to data quality, informing decisions about technology, and encouraging collaborative design processes that involve participants.

This article accompanies the author's 2016 keynote presentation at the HCI International (HCII) Conference in Toronto, Canada. Therefore, much of the discussion of HCI and biodiversity citizen science is seen primarily through the lens of research in the author's laboratory while also respectfully citing others. Given space limitations and the sheer volume of research being carried out in HCI and citizen science around the world, it is inevitable that some important research will be missed. I hope this research and other ideas will surface in discussions at the conference and online.

The organization of the article is as follows. Section 2 provides an introduction to citizen science and HCI. The heart of the article follows by presenting four research challenge areas: Communities (Section 3), Data (Section 4), Technology (Section 5), and Design (Section 6). Section 7 offers a research agenda for each area that leads to a fifth grand challenge—Saving Our Species (SOS). Section 8 presents a conclusion and call to action. Figure 1 provides a schematic representation of this structure.

2. Background: Related Research

2.1. Citizen Science

Projects that involve citizens often continue over longer periods and have a larger scale and scope than professional scientists could typically achieve alone (Bishop, 2014) because of the short-term nature of scientific research funding. Involvement of citizens in science is also helpful because of the dearth of scientists in some research areas. In contrast, there is a large number of citizens who, if motivated, can contribute to different types of scientific projects across the world. The availability of increasingly sophisticated smartphones, particularly those with high-resolution cameras, has encouraged interest in biodiversity and nature projects.

Table 1. Examples of citizen science projects from outside of North America and Europe.

Project type	Brief description	County and URL
Leatherback turtle conservation	Volunteers observe the turtles, guard them, and collect data. Many of the volunteers are tourists who come to Costa Rica for its nice beaches and wildlife and they agree to participate in data collection.	Costa Rica biosphere-expeditions.org/costarica
South American biodiversity data collection	Volunteers map and explore South American Wildlands. Data is collected for Pacific Biodiversity Institute and tourists are encouraged to become volunteers on some projects.	South America pacificbio.org/helpout/volunteer-south-america.html
Southern African Bird Atlas Project2	This conservation initiative claims to be the most important in the region because mapping the ranges of the bird species enables scientists to see changes in distribution. The project is a partnership between the Animal Demography Unit at the University of Cape Town, BirdLife South Africa, and the South African National Biodiversity Institute (SANBI).	South Africa, Lesotho, Botswana, Namibia, Mozambique, Swaziland, Zimbabwe, Zambia sabap2.adu.org.za/
Monitoring air pollution in China	The FLOAT Beijing project collects air quality data by attaching sensors to citizens' kites. Kite flying is a popular pastime so citizens are willing to participate in the project.	China wilsoncommonslab.org/2013/01/28/kite-sensorship-citizen-science-monitoring-chinas-skies-for-pollution/
Fighting invasive species in the forests of South Africa	The scientific purpose of this initiative is to discover new species of *Phytophthora* that are native to forested areas of South Africa so that they can be controlled before they create too much damage. Parents are encouraged to volunteer with their children and to learn together as well as help collect data and support conservation.	South Africa experiment.com/projects/discovering-plant-destroyers-in-south-africa-with-citizen-science

As Silverton (2009) points out, citizen science is not a new concept; crowdsourcing technology just enables more people to connect via more projects over greater distances than ever before. Participation in citizen science dates back to before the days of Darwin when gentleman and lady naturalists collected, carefully named, and cataloged animal and plant specimens for museums or for their private collections. Enthusiasm for nature, particularly in the Victorian era, spawned groups of people who were interested in all kinds of nature, from butterflies to mushrooms, to liverworts, and especially birds. One of the first large-scale citizen science activities predating computer technology were bird counts. The Audubon Society celebrated 100 years of Christmas bird counts in 2015, and in Britain, the tradition is even older. In the early days, these counts involved shooting and killing the birds, lining them up on the ground, and counting them. Thankfully, this practice has stopped in many parts of the world as guns are replaced by cameras. Cornell Laboratory of Ornithology also has a long and impressive history of studying bird behavior, physiology, and demographics since its founding in 1915 and continues to be a leader in citizen science, with 200,000 individuals contributing to its citizen science projects last year (2015), and an average of one million bird observations reported through one single online platform, eBird, each month (www.birds.cornell.edu).

There are a wide variety of citizen science projects, ranging from analyzing stars in the galaxy (e.g., Galaxy Zoo), to water monitoring (e.g., Creek Watch), to phenology (e.g., Project BudBurst), and to reporting biodiversity observations (e.g., iSpot, iNaturalist, NatureNet). Public participation is strong for scientific research and education and for environmental advocacy, but there are concerns about data quality, responsibility, and transparency from all projects and especially those with an advocacy focus ("Rise of the citizen scientist," 2015). CitSci.org lists citizen science projects, and Scistarter.com lists more than 1300 citizen science projects and recreational activities covering all manner of things that occur on the beach, at home, online, etc., with a long directory of topic areas. Searching for biodiversity or nature brings up projects about Butterflies in Kyrgyzstan, Ecuador, and Canada; Landmark Trees of India; and the Atlas of Living Austria, and other parts of the world as well as North America and Europe. The European Environment Agency has logged 115 biodiversity projects in 24 countries (http://www.eea.europa.eu/themes/biodiversity/biodiversity-monitoring-through-citizen-science) and searches on the web reveal many more. Some large American-based and UK-based projects that attract volunteers from across the world are discussed later. Table 1 contains a small sample of projects based in other parts of the world. Some of these ingenious projects engage tourists as volunteers.

Citizen science projects can take different forms. Bonney and his colleagues describe three modes of participation (Bonney et al., 2009):

(1) *contributory projects*, which are designed by scientists with citizens primarily taking the role of data contributors;
(2) *collaborative projects*, which are designed by scientists with citizens taking on roles that involve refining the project design, analyzing data, and disseminating findings, in addition to collecting data; and
(3) *co-created* projects, which are designed by scientists and citizens working together on most, if not all, steps in the scientific process.

Building on this framework, these researchers and their colleagues (Shirk et al., 2012) added two more categories of citizen science projects:

(1) *contractual* projects, in which communities ask professional researchers to conduct a specific scientific investigation and report on the results; and
(2) *collegial* contributions, in which non-credentialed individuals conduct research independently with varying degrees of expected recognition by institutionalized science and/or professionals.

Another approach is provided by Haklay who describes a framework for participation in developing countries that takes a bottom-up approach to involving local people and pays particular attention to power structures and local culture (Haklay, 2013a). Research on virtual geographic information systems provides the broader context for this approach.

The Internet and associated digital technologies, particularly smartphones, digital cameras, sensing devices, and social media, are increasingly used by citizen science projects. These days citizen science tends to involve many people either co-located or distributed across time and space supported by digital technology, which is known as "crowdsourcing." In many respects, the actual data collection via technology is similar to data collection via pencil and paper; it is just conducted at scale involving many people, often across distances, with the potential to produce huge amounts of data. An advantage of technology-supported crowdsourcing done at scale like this is that it creates diverse groups of people with the potential to outperform groups of experts by leveraging multiple viewpoints (Hong & Page, 2004). But data collection via technology is different from data collection through pencil and paper. For example, being able to upload and share observations in real time prompts questions about how increasing participation compromises the privacy of citizen science volunteers because of the ease of capturing and sharing location data and users' account information.

Citizen science projects fulfill different purposes (Dickinson & Bonney, 2012; Wiggins & Crowston, 2011). Action projects employ volunteer-initiated participatory action research to encourage participant intervention in local concerns (i.e., advocacy). Conservation projects address natural resource management goals, involving citizens in stewardship for outreach and increased scope. Education projects make education and outreach primary goals; other projects focus on scientific investigations. These projects can be entirely online (e.g., Oxford University's original citizen science project, Galaxy Zoo) or they can be firmly place-based, often reflecting deeply rooted local interests. These days many projects fall somewhere along this online to place-based spectrum and make use of technology (e.g., email, web, etc.) for communication and coordination. Many also use technology for data collection and data analysis, as well as other purposes, such as mapping (Wiggins & Crowston, 2015).

Increasingly citizen science is conducted with educational goals, including individual learning, and for purposes including the creation of a more informed and active citizenry (e.g., Irwin, 1995), but regardless of the type of project and the medium used for data collection (paper and pencil or technology), citizen science relies on the involvement of citizens. Without citizen involvement, citizen science projects simply do not exist. From a scientific standpoint, data collected and passed on to scientists must be reliable; otherwise, the data is useless. Projects that raise awareness and educate participants may be more concerned initially about engaging participants and making them aware of the benefits to themselves and to society. While they want participants to generate quality data for scientific use, this concern comes later. Biodiversity monitoring tends to be a "contributory" form of citizen science and places more emphasis on scientific outcomes or conservation outcomes than other types of citizen science.

Since one of the key reasons why citizens become engaged in citizen science is self-interest (Nov, 2007; Raddick et al., 2010; Rotman, 2013; Rotman et al., 2012; Rotman, Hammock, Preece, Boston, Hansen, Bowser, & He, 2014a), projects that focus on engagement may tend to veer towards environmental education. Science education sometimes involves citizen science activities, as at the UK Open University, home of iSpotnature.org (Silverton, 2009; Silverton et al., 2015), which forms part of formal university biology education courses and informal education using MOOCs. iSpot is also open to citizens who are not involved in courses and volunteers of all ages. The iSpot platform has a flexible design that can be used on any device and it is free and open to people of all ages and abilities. A key aim of iSpot is to build species ID skills.

2.2. Human–Computer Interaction (HCI)

HCI has had a phenomenal impact on our lives through its influence on the products we use, from communications technologies, to mapping and transport systems, to household gadgets, entertainment and more. When asked for examples of inspiring HCI design, Apple's iPhone comes to mind, and so does Google's simple, powerful search box, Disney's and Hollywood's fantastic animations that can challenge us to suspend our disbelief, and many more. Brad Myers described some HCI achievements in his 1996 article (Myers, 1996), and many of these successes are elaborated in current texts (e.g., Preece, Rogers, & Sharp, 2015; Shneiderman et al., 2016). Until recently, the impact of HCI on citizen science has been relatively limited compared with its potential. This is largely because biologists, other scientists, and HCI specialists do not often work together. As technology plays an increasing role in citizen science, the influence of HCI specialists is destined to increase.

Previous research has investigated how technology is being integrated into citizen science efforts, both generally (Rotman, 2013; Wiggins & Crowston, 2011) and within specific projects (Kim, Robson, Zimmerman, Pierce, & Haber, 2011; Maher et al., 2014; Preece, Boston, Maher, Grace, & Yeh, 2016; Sullivan, Wood, Iliff, Bonney, Fink, & Kelling, 2009). Research has also examined the design of adaptable customizable tools (Kim, Mankoff, & Paulos, 2013, 2015) and how learning occurs from a technology and user experience (UX) design perspective (Clegg, Preece, Pauw, Warrick, & Boston, 2016). Scientists themselves are also starting to discuss how to work with app developers and social media experts to develop software that better meets the needs of scientists (Teacher, Griffiths, Hodgson, & Inger, 2013).

Usability was always associated with technology design, with the aim of getting the job done efficiently and with satisfaction. Designing consistent menu items and icons, and ensuring timely feedback, etc., were important. UX takes in these fundamental design issues but is more about social and affective aspects—having fun, being social, enjoying aesthetics, being amazed, and experiencing other emotional responses—all the sexier attributes!

3. Community

3.1. Participation

Citizen science projects can be a focus for community development. People who live in the same neighborhood often bond over a common cause, such as cleaning up garbage from a local stream, or ensuring that their local neighborhood stream is healthy (Boston, Chetty, & Preece, 2015) or advocating to stop runoff from a farm, or to control the impact of a newly planned housing development. Such efforts are strongly tied to a local place (Chandler et al., 2012; Dickinson, Zuckerberg, & Bonter, 2010; Haywood, 2014; Haywood, Parrish, & Dolliver, 2016; Manzo & Perkins, 2006) and generally build on established ties and issues (Loss, Loss, Will, & Marra, 2015), but these days they usually have a virtual component too—often a website with communications capabilities and/or a Facebook page so that participants can post pictures, comment on postings by others, report sightings, coordinate meetings, and so on.

Other communities come together through a shared interest but operate mainly online because their members are geographically distributed. Within far-reaching networks, subgroups can form that are place-based with a strong local flavor. These days citizen science and its associated societal and community infrastructure can range from virtual to place-based, with every degree of both aspects in between. A large body of literature addresses issues across this spectrum of community development using digital media in various ways (e.g., Gee, 2015; Kraut, Resnick, & Kiesler, 2011; Preece, 2000; Wenger, 1999). The term "communities of practice" describes communities that develop around a particular practice (Wenger, 1999) that was often related to work (e.g., science, education, business). Preece (2000) used the general term of "online community" to describe groups that were almost entirely online in the mid- to late 1990s. "Communities of interest" emerged as a useful term for talking about communities that focused on interests that were not formalized within a work context, such as environmental and citizen science community projects for advocacy, awareness raising, and interest in nature. Gee's work on affinity spaces is also influential for describing how flexible learning communities with porous borders develop (Gee, 2015).

Another framework for thinking about communities that use technology to promote interaction among participants is the reader-to-leader framework (Preece & Shneiderman, 2009). This framework describes the processes that individuals go through, starting with an interest in a topic that they read about that draws them into the community, to gaining confidence to make a minor contribution such as correcting an error and then making more substantial contributions, to collaborating together. Some participants may even go on to become leaders. Behavior often varies within a community depending on how well one's suggestions are received and the topic being discussed. For example, a member of a citizen science project might become an expert or even leader of a local bird community, but only be an occasional contributor when plants are being discussed, and may not venture any comments when mosses and ferns are the topic of discussion. While this framework was not developed to describe citizen science projects *per se*, it can be used to model and describe individuals' behaviors in citizen science communities. Understanding what motivates citizens to participate in citizen science projects provides another lens for examining citizen science communities.

3.2. Motivation

Volunteers and scientists derive different benefits from their involvement. Technology has enabled scientists to benefit from getting the help of hundreds, thousands, and sometimes millions of volunteers at little or no cost. The benefits for volunteers are much more varied and are often related to personal interest (Jennett et al., 2016; Nov, 2007; Raddick et al., 2010; Rotman, 2013; Rotman et al., 2014a, 2014b; Rotman et al., 2012). They may be motivated by local or national causes such as supporting research on monarch butterfly populations, or by becoming involved with organizations such as the World Wildlife Fund (wwf.org). Such organizations operate at many levels: they educate, conserve, contribute to science, and politically persuade governments around the world to change their policies. Amazing individuals such as the UK's David Attenborough, Harvard biologist Edward O. Wilson, and Hollywood celebrities have the stature and charisma to draw attention to projects that they associate with.

From an analysis of questionnaires and 44 semi-structured interviews with scientists and participants in the United States, India, and Costa Rica, Rotman found that volunteers initially join a project because of self-interest (Rotman, 2013; Rotman et al., 2014a, 2014b, 2012). These interests might be roused by a hobby or potential for reputation gains that bring career advancement and status. Whatever the reason, self-interest was a common theme, as these quotes illustrate (Rotman, 2013):

> "I think personal interest comes first. Personal interest and personal gain, with information." (Jill, United States, *Personal Interest*)

> "…it will benefit me to increase my knowledge and … for my experience for my future prospects or any other." (Abhinav, India, *Self-promotion*)

> "A volunteer can participate at any level of research in my opinion. From a person who has no experience and needs to be trained to participate, to someone who has the same academic qualifications as the scientists and who just isn't being paid." (Laura, Costa Rica, *Self-efficacy*)

This occurred most often among participants from Costa Rica, where volunteers often got to control their own and other people's data. This was not allowed in the United States and India.

> "I think if you visit Costa Rica and you talk to a cop, driver, or maybe a bus driver or people that work in a restaurant, they will make you a conversation about the topics of environment and their importance, there's a true moral thing." (Jose, Costa Rica, *Social responsibility*)

While self-interest was important for drawing people into a project, the real challenge for scientists and project leaders is understanding what brings a person back again, not just once, but many times as a continuing contributor, whose skills improve with ongoing involvement. Understanding long-term participation is one of the secrets to the success of a citizen science project. Rotman (2013) found that the reasons for continuing to be involved in citizen science were rather different from the initial reasons to join. Unlike initial motivations, which focused mainly on benefits to oneself, long-term participation was motivated by relationships that were negotiated with other volunteers and the scientists, both within and outside of the projects. Five factors were found to encourage long-term participation:

Trust was a strong component for both volunteers and scientists. Scientists were frequently skeptical about the accuracy of the data and therefore its value to science. Volunteers reported that the scientists were sometimes aloof and intimidating, and used unfamiliar jargon. Some scientists did not meet with volunteers, which made developing trust difficult.

Setting common goals up front and explicitly creating a baseline of expectations, particularly between scientists and volunteers, was welcomed. Frequent communication also helped to reduce confusion and confirm roles and responsibilities.

Acknowledgement and attribution were essential for motivating long-term participation. Acknowledgement could take various forms, and views about how much and how often to acknowledge varied greatly, but the more the participants felt that their efforts were scientifically validated, the more the acknowledgement was appreciated.

Mentorship was based on several separate but interrelated concepts: training, closeness, and empowerment. Although volunteer training tended to go hand-in-hand with higher quality data and productivity, not many scientists got involved in training volunteers.

External relationships were valued, because although most volunteers were drawn to citizen science for personal interests, they saw the impact that it could have on the environment, and also how it impacted others and promoted collectivist relationships. Education was also an important vehicle for promoting these relationships.

In a recent questionnaire and interview study of participants in the online citizen science sites Foldit and Planet Hunters, Curtis found that the more complex the site, the greater the likeliness that volunteers would participate and collaborate with others. High levels of participation by others and being able to contribute were strong motivators (Curtis, 2015). In another study, it was found that newcomers to zooniverse form clusters when they are unsure what to do and have little access or clues about the previous work done by others (Jackson, Osterlund, Maidel, Crowston, & Mugar, 2016). Two types of behaviors were observed in Jackson et al.'s study: some volunteers focused on contributing but made few comments; the other group exhibited the reverse behavior: they made lots of comments but contributed very little that was new (Jackson et al., 2016). More research is needed to see if this interesting finding generalizes to biodiversity citizen science communities.

Learning seems to be strongly related to personal interest, which also motivates scientific literacy (Crall et al., 2013). Similarly, creativity is also a motivator in some kinds of citizen science. "Creativity seems to be strongly related to engagement: it can optimize both an individual's activity and the project itself" (Jennett et al., 2016, p. 18). These authors present a thematic map of motivation in which they call out curiosity, interest in science, and a desire to contribute to research as primary motivations for initial participation. Continued interest, ability, and time are listed as motivators for sustained participation (Jennett et al., 2016). These contrast somewhat with the detailed list presented by Rotman (2013). This may be due to Jennett's team working with a different type of citizen science projects—online or cyberscience projects. Jennett and her colleagues also present thematic maps for learning and for personal creation. They note that learning in citizen cyberscience tends to be informal, unstructured, and social.

While Rotman found that a variety of motivational factors encourage participation, demotivating factors also affect participation, especially long-term participation. Attrition rates among volunteers in her study were estimated to range from 80 to 95%. Time constraints and problems with technology were the most prominent demotivating factors. Jennett et al. (2016) also mention that the time needed to participate was a finding in their study, though they do not report lack of time as such a negative demotivator. Complex tasks and the need to travel to remote areas were mentioned as time-sinks in Rotman's study (Rotman, 2013). Technology had the potential to facilitate projects, but in practice it often failed, causing much frustration and wasting time. This problem was particularly apparent in India and Costa Rica, where technology infrastructure, particularly Internet access, was poor during the 2011–2012 study period (Rotman, 2013).

Even in the technologically advanced United States, citizen science projects experience problems with Internet and communications technology (ICT) (Wiggins, 2013). Location can impact technology access, particularly Internet access. In the United States, many citizens rely on public libraries for Internet access, which are usually better equipped in urban areas than in suburban and rural areas (Bertot, Jaeger, & McClure, 2011). A 2015 Pew Research Center study (Perrin & Duncan, 2015) reports that 84% of all U.S. adults use the Internet, but there are differences across age groups, ethnicity, and educational and socioeconomic levels. Young people tend to be more avid users than older people, as might be expected (96% of 18–29 year olds; 93% of 30–49 year olds, 81% of 50–64 year olds, and 58% of those 65+ use the Internet). Blacks and Hispanics lag behind Whites (78% of Blacks, 81% of Hispanics, and 85% of Whites reported Internet use). Less well-educated and poorer Americans lag behind better educated and wealthier Americans. People in other remote areas of the world also suffer from lack of Internet access (see for example Haklay's (2013b) work on virtual geographical information systems).

In practice, according to Toerpe (2013), typically people who get involved in citizen science tend to be middle aged, middle income, and usually have some college education. More women than men tend to become involved, but it depends on the topic, and in the United States, most participants are Caucasian. Citizen science project leaders that are mindful of these differences can take action to support diversity (Purcell, Garibay, & Dickinson, 2012) by developing projects in racially mixed neighborhoods and encouraging local leaders to step forward from the community. Offering paper data collection sheets as an alternative to entering data via a smartphone may appeal to those who do not like technology or do not own a smartphone. If the paper data collection sheets are administered by a trusted third person who then transfers the data into the digital system, this can have the added advantage of checking the data quality (Kelling, 2012), especially as people who take on this role are often experts. Younger participants may be enticed to participate by games and competitions.

Taking a different perspective, citizen science communities can be viewed as loosely constructed learning communities. Gee (2005) introduces the idea of affinity spaces, locations in the physical or virtual world (or both) in which people interact around a common passion or interest with others who have diverse expertise and experiences, taking on different roles and sharing their knowledge, tools, and technologies. Participants teach and learn from each other—people of all levels of expertise and experience interact and create new projects together, and diverse forms of knowledge and participation are valued. Gaming communities are a familiar example, and citizen science platforms provide another to the extent that they allow members to engage in science deeply connected to their interests and values and provide low-risk opportunities to explore potential roles they might take in science, particularly in life-relevant scientific activities (Clegg & Kolodner, 2014). Stemming from game-based applications, Gee describes how affinity spaces consist of a *rich problem-solving context* and *interest-driven sites* where groups of people organize around their own interests (Gee, 2015).

Affinity spaces are like communities of practice in that they are built around community members' interests, but they are more flexible and porous than communities of practice (Wenger, 1999). They tend to bring together and empower groups of people who would typically not join communities of practice, which they consider to be more formal and often threatening. Gee (2005) specifies three types of diversity needed in affinity spaces to support sustained learning experiences for participants:

(1) people with different orientations to, and expertise in, the domain of interest, who draw from the unique bodies of knowledge that they bring from their respective community experiences;
(2) diverse modes of engagement that enable individuals to take on distinct roles in groups, and different ways of contributing and communicating; and
(3) diverse ways of learning and diverse learning experiences.

Affinity spaces could provide a path to understanding and facilitating whole communities of citizen science participants to cohere around shared goals, particularly as most participants come to citizen science to satisfy a personal interest, which has to be sustained by feedback and community interaction and supported by well-functioning technology that enables getting the citizen science activity done at both individual and community levels. A recently launched project focusing on community-driven citizen science projects (Clegg et al., 2016; Preece, Boston, Maher, Grace, & Yeh, 2016; Preece, Boston, Yeh, Cameron, Maher, & Grace, 2016) is striving to unearth this understanding through a learning sciences perspective. Early results from this project suggest that place-based community activities are an important starting point for this community development, which may eventually be replicated in some vicinities via distributed learning networks supported by technology.

4. Data

4.1. Quality

Scientists depend on high-quality data for the success of their research efforts. When untrained volunteers are involved in collecting and/or analyzing and managing data, it is perhaps not surprising that professional scientists express concern about whether they can trust the data (Rotman, 2013). In addition to training issues, data quality concerns have been linked to uneven levels of expertise, anonymity, insufficient attention to the scientific method, and non-standardized and poorly designed methods of data collection (Hunter, Alabri, & Van Ingen, 2013).

Citizen science projects deal with data quality in different ways. Many try to help participants to collect data accurately by offering training, particularly for more complex tasks like water monitoring (Sheppard & Terveen, 2011). When the data is a photograph or text that is captured in the field and entered directly into a citizen science app such as iNaturalist (iNaturalist.org) or iSpot (ispotnature.org), two citizen science projects that collect nature observations, there may also be instructions to help guide the process. For example, many projects (e.g., eBird, a project of the Cornell Laboratory of Ornithology that collects data on bird sightings) encourage the uploading of photographs, which can help with identification. A photo taken with a good camera and uploaded via a laptop is likely to be better than one taken with a smartphone. Nevertheless, whatever the quality, photos may contain detail about the habitat that is helpful for identification. Some projects, like eBird.org, have volunteer coordinators that use photos to help validate different observations. Smartphones also collect useful information automatically, including GPS location and date and time of the data collection.

eBird's sophisticated method of validating data quality is worth a closer look because it represents the state of the art for a mature citizen science project with global reach and extensive participation. Once submitted into the eBird system, the data is checked for accuracy before being made available as trusted scientific data for use by researchers. This is done by a combination of digital filtering and human experts. For very large projects such as eBird, which received more than 9.5 million observations from around the world in a single month (May 2015), having digital filtering systems take the first pass through the data to identify obviously questionable data is essential. For example, if a pink flamingo were spotted on the beach at Aberdeen on Christmas day, this would be flagged as suspect—perhaps the observer enjoyed too much Scottish whiskey! Flagged data is checked against other reports from the same geographical area and may also be passed to a human expert for review.

The filtering system also prompts the observer for additional information that encourages reflection before the sighting is submitted. For example, if a bird is not normally seen in the location where it is recorded, or is not present at that time of year, or the number of birds reported is unusually high, then the birder is asked to provide more information about the sighting.

A team of more than 500 expert birders helps to confirm or refute observations that are flagged by the filtering system. These experts are identified based on their birding record in eBird in the geographical area in which they make observations. If an expert goes to another area, perhaps on vacation, he or she is not awarded expert status until the record from the new area provides evidence of competence. Although eBird reports that tens of thousands of mistakes are made every year, eBird has an impressive record of producing quality data that is used by scientists and citizens across the world. Once data is accepted into the data repository of a project like eBird or iNaturalist, it may then be submitted to a larger aggregation repository such as the Encyclopedia of Life (eol.org) or the Global Biodiversity Information Facility (GBIF.org) so that it can be pooled and made more widely available. GBIF also shares data with EOL, with the aim of making its data as widely available to others as possible.

4.2. Sharing, Aggregating, and Archiving

The Encyclopedia of Life offers another approach to the challenge of ensuring data quality because it relies on a combination of professional and volunteer curation as well as vetting through a network of content partners. March 2007 was an exciting time for biodiversity science. After receiving a prize for his TED talk, visionary biologist Edward O. Wilson made an impassioned plea on behalf of all the world's creatures. He advocated for us to learn more about the organisms that we share the planet with by building a networked encyclopedia of all the world's knowledge about life on earth. He pointed out the obvious—that in this time of species extinction how could we possibly know what we were losing if we don't know what is there in the first place.

The MacArthur Foundation generously stepped forward with initial funding to create EOL, and other donors followed. The goal for EOL was to develop a webpage containing text, photographs, and statistics, accurately curated for every living species in the biosphere. This ambitious goal was particularly challenging as scientists do not agree on how many organisms and therefore webpages are needed. Some say that there are potentially 3.5 million distinct pages needed, of which Cynthia Parr and her colleagues reported that EOL has developed 1.3 million pages with some content (Parr, Wilson, Leary, Schulz, Lans, Walley, Hammock, Goddard, Rice, Studer, Holmes, & Corrigan, 2014). Others scientists say the number of species is much higher, and predictions vary wildly, ranging from 5 million to over 100 million (Wilson, 2016) As of this writing, EOL reports that its 1.3+ million species pages include 3.3 million images, 5500 videos, and 6000 audio recordings. More than 86,000 people have signed on as members, and they have created more than 250 communities and 9500 collections based on their interests (http://eol.org/statistics).

Data showcased on EOL comes from more than 320 content partners, as recorded in March 2015, and that number is still growing. These are organizations that have developed partnerships with EOL. Developing these partnerships involves the partner and EOL in agreeing upon data standards and processes for transferring data to EOL. He (2016) categorizes these partners as:

(1) *venerable organizations* of established, highly reputable organizations with long histories of 70–250+ years that transfer thousands of data items on a regular basis;
(2) *professional repositories* that also have a trusted history and may be located in universities, government agencies, etc.;
(3) *citizen science initiatives* such as iNaturalist that strive to ensure quality data collected by citizen volunteers;
(4) *social media platforms* like Flickr, YouTube, and Wikipedia;
(5) *education communities* that may get involved in bioblitzes or other projects; and
(6) *individuals* who have a passion for collecting data about a particular group of organisms (e.g., butterflies, mosses, bees, etc.)

On reaching EOL, the data is professionally curated by EOL-appointed staff, all of whom are professional biologists. In addition to noting the accuracy of the taxonomic data, credit is given to the data owners, who may ask for creative commons licenses for their photographs. While transferring data from one data repository to another might seem simple in this age of fast computers, there are many sociotechnical issues to be resolved (He et al., 2016). Considerable time is needed to develop fruitful relationships that lead to partnership agreements and agreed-upon data transfer processes. When the data comes from citizen science projects, it is especially important that it can be trusted by the scientists, who look to EOL for research data. Technical data infrastructure, while important, can only do so much. People's skills, patience, and ability to form good interpersonal working relationships are absolutely essential for the successful data sharing needed to make EOL valuable for scientists and citizens alike (He et al., 2016).

While a few project leaders understand what motivates citizens to participate in citizen science and to ensure scientific research level data, there may be a trade-off for small projects without much infrastructure between increasing the number of participants in a project and ensuring the quality of the data produced. Encouraging nature preserve visitors to submit pictures taken with a cell phone might motivate participation, but might also produce poor-quality data (Preece et al., 2016b). Finding a balance between motivating participation while also ensuring data quality can be tricky and requires further research.

5. Technology

5.1. Deciding Which Technology to Use

Emerging technologies influence the scientific research process by streamlining data collection, improving data management, automating quality control, expediting communication (Newman et al., 2012), and encouraging data sharing. Technology opens the door for broader public participation, community development, and education. But making good technology choices can be challenging and expensive. Users of any system perceive trade-offs between the value they receive and the effort they expend (Fischer, 2011b). Some key questions to consider are: *Who will use the technology; What will they use it for?* and *Where they will use it?*

Who uses it? In citizen science projects, there are at least two types of participants: scientists and citizens. Within each type, there is potential for considerable diversity, particularly among citizens in terms of age, gender, experience, race, education, and the language used for communication. Of course, these groups are not exclusive. For example, many citizen science volunteers also have professional training and experience.

What for? There are many reasons why people create or participate in citizen science projects. Scientists want help collecting data and participants join for self-interest as mentioned earlier. Most participants contribute data in the form of photographs, comments, scientific readings, etc.; some also analyze data; some are data consumers and want to use the data; and many do a combination of these things and also help to lead projects and help other participants.

Where? The majority of projects occur on land, but some require special technology for collecting data in freshwater and ocean habitats. Even those on land may need covers, etc. to protect technology from getting wet in the rain or from being dropped on hard surfaces. Technology that is going to be exposed to the weather for long periods will also need protective casing. Biodiversity monitoring projects frequently require participants to go to remote areas where wifi coverage is poor, which is discussed later.

To focus the discussion that follows, the vast array of citizen science projects in existence will be grouped under just two headings: those that actively involve humans in collecting data —“active data collection projects”—and those that only require humans to set up the data collection technology and do not require humans to be present—“passive data collection projects.” Examples of active data collection projects include those that use smartphones and cameras, etc. for data collection such as iSpot and iNaturalist. Examples of passive data collection projects include projects that use sensors, webcams, and tracking devices that are set up by scientists to collect data. Both types of projects may involve citizens in analyzing data. Significant UX issues are summarized at the end of each section.

5.2. Active Data Collection Citizen Science Projects

Silverton et al. (2015) report that while attention to biodiversity and biodiversity education has increased dramatically due the development of new tools, the ability of biologists to accurately classify organisms has lagged behind. This is a problem as all fields of biodiversity science rely on accurate classification. Crowdsourcing by involving citizen volunteers is an attempt to solve this problem.

With little effort, many citizen science apps can be downloaded from Apple and other online app stores in a matter of minutes for free or for a small fee. These apps take advantage of the functionality provided by the smartphone manufacturers that typically includes a camera with a range of capabilities, including creating videos, geopositioning software (GPS), maps, and date and time logging software. These can be enhanced for particular citizen science projects to include identification guides, tutorials, mentoring, and carefully designed activities to motivate participation and support learning. Some projects enhance the experience for participants by designing integrated platforms that usually include a website and sometimes other technology too. For example, NatureNet (nature-net.org) offers smartphone apps (iPhone and Android) that are chiefly for collecting biodiversity data that is automatically uploaded to a tabletop computer and website. The idea is that the tabletop encourages discussion by local groups standing around the table, whereas the website encourages distributed participation (Grace et al., 2014; Maher et al., 2014; Preece et al., 2014).

iNaturalist.org developed in the United States and iSpotnature.org developed in the UK are discussed next. Both are impressive large projects with international outreach that collect biodiversity data.

5.3. iNaturalist.org

iNaturalist is an open-source biodiversity data collection platform developed in the United States by three University of California, Berkeley School of Information Studies students as a Master’s final project in 2008. In April 2014, iNaturalist merged with the California Academy of Sciences and also celebrated its one-millionth observation.

Who uses it: On May 3, 2016, the iNaturalist website stated that there are 197,286 registered users who have contributed 2,612,073 observations of about 92,450 species.

What for: According to Wikipedia, in 2015, iNaturalist was used in over 2000 projects worldwide, spanning diverse activities from recording individual species to bioblitzes, documenting the spread of invasive species, roadkill observations, universities’ and schools’ field studies, international monitoring of amphibian and reptile species, and more.

Where: Though based in the United States and with the majority of contributors located there, it is used across the world. Increasingly, iNaturalist is seen as a platform that can be used anywhere in the world. Data recording can happen anywhere regardless of wifi or cellular reception. GPS satellite reception is required to obtain coordinates to indicate where observations are made. This is important for verifying observations and representing them accurately on the map.

iNaturalist is a widely distributed community accessed by participants via its website and smartphone apps. The website homepage has dynamic information windows providing the

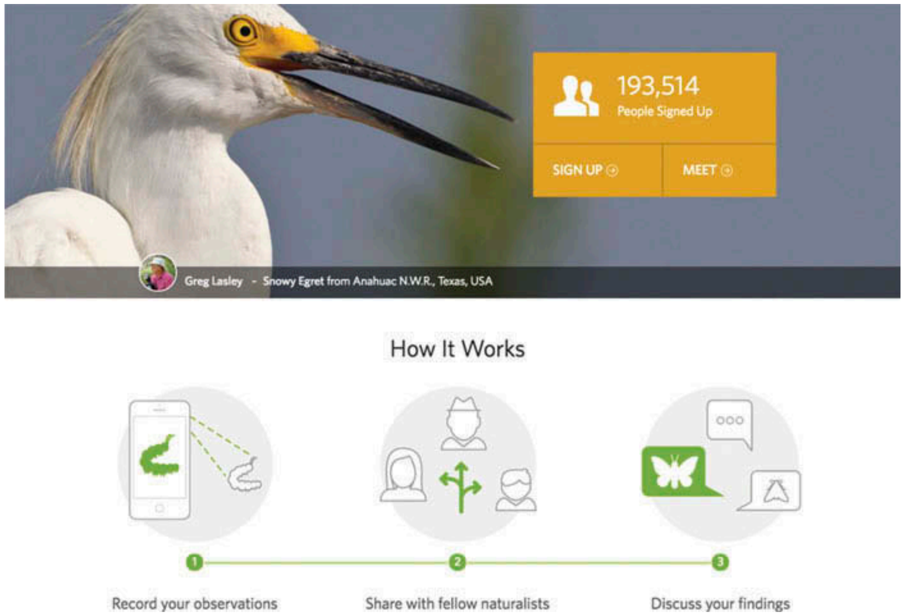


Figure 2. Homepage of the iNaturalist.org website.

latest statistics, plus the usual signup and login information (Figure 2). Information about what users can do is provided in a panel titled "Nature At Your Fingertips" with six icons and brief descriptions (Figure 3). Participants are invited to keep track of their sightings, connect with experts in the community (and become an expert) to identify organisms, learn about nature, become citizen scientists, and run bioblitzes.

After logging in, users are invited to explore, read iNaturalist news, observe (which mostly involves taking and submitting pictures), or get information from online plant and animal guides. iNaturalist is strongly map based and features projects and data collected close to one's own location. Tapping on a photograph (i.e., data) expands it and shows the location and date and time of submission. The community of users can add comments, help with identifications, and offer additional pictures. In the author's experience, other participants are very quick to help with bird identifications, but less so with plant identifications (also reported by Wiggins & He, 2016). Through a support network, iNaturalist has created a community of naturalists. There are leaderboards (Figure 4) detailing who has provided observations and on how many species. For example, on May 4, 2016, a user called "finatic" is listed in first place on the main leaderboard with 39,998 observations of 5124 species. Finatic is a nature photographer, who also has curator status. He has many followers and frequently helps others with classifications. The leaderboard includes the top 500 contributors. The person in the five hundredth position has contributed 842 observations of 97 species! The leaderboards add an element of challenge that may be liked by some contributors, though others may find it daunting (Massung, Coyle, Kater, Jay, & Preist, 2013; Preist, Massung, & Coyle, 2014).

iNaturalist has clear policies about how participants should behave, particularly with reference to commenting on others' contributions, and malicious behaviors are not tolerated. So far, iNaturalist distinguishes expert or non-expert users according to information provided on the users' profiles. iNaturalist does not have an independent way of judging expertise, but it does distinguish between different levels of

Figure 3. iNaturalist.org, "Nature at Your Fingertips," showing the different activities available to participants.

Figure 4. iNaturalist.org leaderboards.

quality for the data. Whether a datum is research grade or not is calculated by iNaturalist's automatic data quality assessment algorithm. The term "Research Grade" is the name iNaturalist uses for a state of data quality that they believe is both complete and accurate (though not necessarily precise) and encodes some of their opinions about what kind of information iNaturalist wishes to collect. For example, observations of captive/cultivated organisms are not considered "Research Grade" on iNaturalist because the iNaturalist team wants the site to be about wild organisms. Scientists might use the captive/cultivated data for research if they wish, but it is not the focus for iNaturalist, so they try to discourage it.

He (2016) reports that the minimum criteria to reach research grade (updated on August 2015) is that a datum must have:

(1) a community-supported identification with a taxon level lower than family;
(2) a digital voucher (i.e., the media data element, such as photograph or audio);
(3) a plausible observation time and location; and
(4) no disagreement from other iNaturalist community members.

An observation that does not reach research grade is classified as either "needs ID" because it needs more identifications or "casual" because it does not meet enough of the requirements to become research grade.

iSpotnature has similar overall goals to document and support biodiversity science, but it also has an explicit education mission.

5.4. *iSpotnature.org*

A team from the UK Open University created a digital, networked platform known as iSpot and later as iSpotnature (Figure 5). Development began in 2008 with the goal of creating a sociotechnical system to support crowdsourcing biodiversity data collection while at the same time educating students and the public about biodiversity (Silverton et al., 2015).

Who uses it: In May 2016, iSpot had over 57,000 registered participants worldwide. iSpot is integrated into MOOCs and more formal UK Open University undergraduate biology courses as well as being open to researchers, citizen participants, and more than 2000 projects.

What for: Participants submit biodiversity data, mostly photographs, to iSpot. As with iNaturalist, a community infrastructure encourages participants to help each other to identify their observations, provide feedback, and gain a reputation.

Where: The largest concentrations of users are in the UK, Europe, and South Africa. Many are involved through partnerships with iSpot UK (e.g., South Africa).

In 2014, iSpot reported crowdsourcing the identification of over 30,000 taxa, of which >80% were classified at the species level. A large number of these received a classification within an hour of being submitted. As in most citizen science projects, the majority of participants are not trained in biodiversity science, which raises questions about the quality of the data. Therefore, Silverton and his colleagues had to develop ways to ensure data quality that would be trusted by scientists and educators (Silverton et al., 2015). To achieve this goal and also to help create a community of citizens, researchers, and educators, iSpot uses a nine-dimensional reputation system designed to motivate and reward participants.

An algorithm awards reputation points to a participant who proposes an identification that achieves agreement from other participants. The level of reward given to the person making the suggestion depends partly on the agreers' own reputation scores for the particular taxon (e.g., amphibians and reptiles, birds, fish, fungi and lichens, invertebrates, mammals, other organisms, plants, all groups; see Figure 6.) Three considerations are built into the algorithm: the expertise of the person offering a classification, which takes account of both accuracy of previous determinations and formal qualifications; the number of determinations contributed; and a hybrid of these two designed to enable participants to learn and improve. The authors report that "… this system is able to discriminate effectively between competing determinations when two or more are proposed for the same observation. In 57% of such cases, the reputation system improved the accuracy of the determination, while in the remainder, it either improved precision (e.g., by adding a species name to a genus) or revealed false precision, for example where a determination to species level was not supported by the available evidence" (Silverton et al., 2015). They suggest that iSpot's success is largely due to its social network, which includes novices to expert scientists.

Figure 5. Homepage of the iSpotnature.org website showing photographs that participants have submitted and the nine-dimensional reputation system represented by small icons.

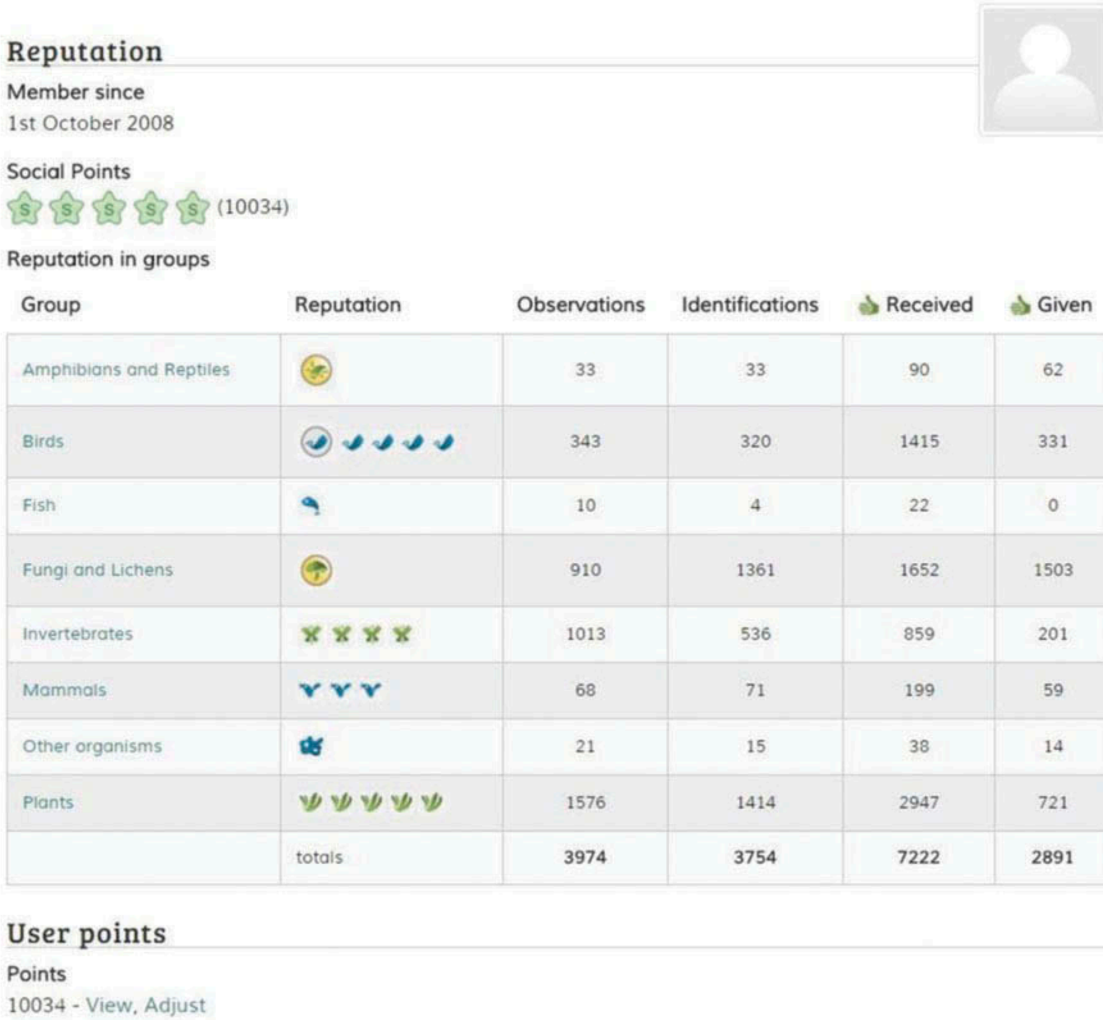
Reputation is shown on participants' personal pages. Up to five badges can be acquired in any of the nine categories. A participant could be an expert in identifying birds and a novice in identifying fish, and have an intermediate rating for identifying plants. Silverton et al. (2015) point out that the reputation and badging categories are based more on what seems most appropriate for dealing with the flow of incoming data submitted by participants than on a formal biological taxonomy. They needed a number of categories that covered the spectrum of taxa without there being so many that the system was confusing for participants.

To check the accuracy of the classifications, the iSpot team submitted 46,736 observations of plants and moths made in the UK to the biological recording website iRecord run by the UK Biological Records Centre (http://www.brc.ac.uk/irecord). A sample of 2234 plants and 1053 moths were examined by the experts in iRecord, and 94% of the plant records and 92% of the moths were verified as correct (Silverton et al., 2015).

Key UX Issues and Questions Raised by Discussion of iNaturalist and iSpot

iNaturalist and iSpot are both successful platforms with different missions and histories.

(1) How do the differences in iNaturalist's and iSpot's infrastructures reflect their differences in the missions of these two platforms?
(2) Do leaderboards support community? If so, for whom? Are some people deterred from participating?
(3) How do the two data validation systems compare for ensuring data accuracy? What are the benefits and drawbacks of each?
(4) iNaturalist appears to be used in more countries across the world. Why might this be?
(5) The key aim of iSpot is to build species ID skills so that everyone who uses iSpot can learn. The community-oriented reputation system helps to achieve this goal. How does this system differ from that of iNaturalist?


Reputation

Member since

1st October 2008

Social Points

(10034)

Reputation in groups

Group	Reputation	Observations	Identifications	Received	Given
Amphibians and Reptiles		33	33	90	62
Birds		343	320	1415	331
Fish		10	4	22	0
Fungi and Lichens		910	1361	1652	1503
Invertebrates		1013	536	859	201
Mammals		68	71	199	59
Other organisms		21	15	38	14
Plants		1576	1414	2947	721
	totals	3974	3754	7222	2891

User points

Points

10034 - View, Adjust

Figure 6. A member page from iSpotnature.org showing reputation badges. © Janice Ansine. Reproduced by permission of Janice Ansine. Permission to reuse must be obtained from the rightsholder.

5.5. Passive Data Collection Citizen Science Projects

Passive data collection involves little or no human intervention once the technology is set up until the data is available for analysis. The exception is when something goes wrong, and human intervention is needed to fix a problem, for example, the tracking collar on an animal comes off. Participants, such as park wardens with specialist expertise, are often involved in the planning, design, and implementation of the projects. Other citizens may be involved in analyzing data, but in general, sensing technologies, fundamental to many areas of modern science, have not been harnessed in citizen science to any degree (O'Grady et al., 2016).

Technology used for passive data collections also includes functionality that is embedded in smartphones, such as cameras for taking photographs and video for capturing movement, timing, and sound; GPS to capture location data; automatic time stamping; plus the ability to take notes, send comments, and ask questions in the field and to deal with situations in which wifi or cellular data transmission are not available. Examples of passive data collection technologies include: webcams, sensors, various tagging and tracking integrated into animal collars, and drones that are programmed to collect data continuously.

Who uses it: Scientists and sometimes other citizens experienced in using the devices design, develop, and set them up. Typically, citizen scientists who may or may not also be scientists (e.g., wardens in parks, water monitoring experts, etc.) help technology developers to understand the context of use. These citizens and less experienced volunteers may also become involved in data analysis.

What for: These devices are typically used to collect data remotely in places and situations that were hitherto difficult to reach. For example, they might be used to map remote areas of rainforest, or to learn the migration habits of animals or the behavior of predators as they track their prey.

Where: They may be used anywhere, but they are especially useful in areas which are difficult to get to (e.g., rainforests, Haklay, 2013a) and where data is often collected over long periods of time (e.g., seasonal recording of tree phenology) or for tracking animals which travel over large distances (e.g., migrating whales or zebra), or where observation is difficult (e.g., rare carnivores such as snow leopards).

5.6. Sensors

Sensors have had an important role in scientific monitoring for many years, and inexpensive computer-controlled technology is popular in citizen science for recording temperature, pH, and for timing events. In the Creek Watch project, an app was designed for assessing the water quality of creeks. The project involved specialists from government organizations who were responsible for regulating water use, wastewater discharge, and pollution at state, regional, and city levels; private groups that included consultants who worked closely with government agencies to conduct evaluations for environmental permits; and volunteers who picked up trash and monitored the water (Kim et al., 2011). Other projects that make use of sensors include voluntary weather networks such as the UK Rain project (Illingworth, Muller, Graves, & Chapman, 2014) and Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) in the United States (Cifelli et al., 2005).

Within the field of HCI, a seminal paper by Saul Greenberg and Chester Fitchett (2001) about Phidgets—sensors and timed switching devices—helped lay the groundwork for the maker movement. The authors define phidgets—physical widgets—as having the same relationship to physical user interfaces as graphical user interfaces (GUIs) do to user interfaces. Evaluation of the devices by undergraduate computer science students demonstrated that: (i) phidgets were simple enough for developers to use, modify, and recombine into more complex devices without getting into low-level device construction and implementation; and (ii) were easy enough for the average programmer to program and extend, although many HCI specialists and citizen scientists would have found doing this challenging. Since Greenberg's and Fitchett's work was published (Greenberg & Fitchett, 2001), the role of sensors and other devices for remotely collecting a whole variety of data has increased. Science projects that use sensors include long-term monitoring of water and air, and some kinds of animal tracking. Partnerships between scientists and citizen scientists on these and other projects are likely to increase (Newman et al., 2012) as technology becomes easier to use and less expensive. For example, more recently, Arduino and other companies are helping to promote sensor-based projects by selling a wide variety of easy-to-use phidget-like devices that can be assembled into modules. Scientists and enthusiasts who want switches to take pictures, turn on lights, or collect samples at timed intervals can now build their own devices or purchase readymade ones from scientific suppliers.

5.7. Webcams

Webcams are now commonplace in hundreds of citizen science projects and are often located in nature centers and national parks for recording animal behavior around water holes and for filming nocturnal animals. Citizen scientists often help with data analysis, particularly the identification of species through photos. One example is the Snapshot Serengeti project of Zooniverse (https://www.snapshotserengeti.org/), in which volunteers are asked to label various animals to assist scientists studying interactions between predators and prey in an ecosystem. eMammal is another example (emammal.si.edu/triangle-camera-trap-survey).

Graham and his colleagues describe how collecting phenology data for plants can be difficult because it is time consuming, sometimes tedious for participants, and thus prone to error (Graham et al., 2009). Visible light digital cameras allow researchers to quantify leaf flush and other parameters at many locations without having to rely on volunteers.

Microphones can also be positioned in the environment for recording sound, for example, communication between groups of orca whales and bird songs.

5.8. Tracking Devices

Bird ringing or banding also has a long history as does tracking monarch butterflies by applying special labels on to their wings. Attempts to track animals to gain a deeper understanding of their behavior have gone on for years, but more recently scientists are looking to advances in technology to make this task easier and more reliable.

Tracking collars are effective data collection devices that are used in a variety of projects for tracking animal migration and other kinds of animal behavior. ZebraNet (Juang et al., 2002) was a pioneering project to track zebras' behavior in Kenya. Around 35,000 zebra from two different species roam over vast areas of the Kenyan plains. The two species have quite different grazing habits. Grevy's zebra form large, loosely bonded herds and Plains zebra form tight-knit unimale, multiple-female harems. Zebra have three different types of behavior: they graze, graze and walk, and they run fast to avoid predation. They spend very little time sleeping, thus reducing their vulnerability to predators. In developing the collars to collect data, these and other behavior characteristics, such as drinking habits and angles of head-moving, were of prime importance for informing the design and determining trade-offs.

The goals of this project illustrate the power of tracking technology for collecting data and the challenges of making it work successfully. These goals (Juang et al., 2002, p. 97) were to:

(1) Collect GPS position samples every 3 minutes.
(2) Collect detailed activity logs taken for 3 minutes every hour.
(3) Operate for 1 year without human intervention (e.g., no re-collaring within the year).
(4) Operate over a wide range (hundreds or thousands of square kilometers) of open land.
(5) Require no fixed base stations, antennas, or cellular service that might attract attention or vandalism.
(6) Have a high success rate in eventually delivering all logged data.
(7) Limit the weight of the zebra collar to 3–5 pounds.

Battery life and energy efficiency were important constraints for this project. The size and behavior of the animals determined the size of collars, which in turn impacted the battery size, so trade-offs had to be made.

A project on badger behavior further illustrates such trade-offs. Since badgers spend most of their time underground, low-power devices that opportunistically upload compressed data in spurts when the animal wearing the collar is in range of a base station were developed (Markham, Trigoni, Ellwood, & Macdonald, 2010). In recent years, many other elaborations have been developed that enable scientists to more accurately predict animal movements. For example, the WildScope project integrates detecting location via GPS and integrating this information with wireless communication, which enables researchers to project movement trajectories (Picco et al., 2015). As with the ZebraNet researchers, there were clear goals for the development of WildScope that included developing different sizes of collar and devices to fit large animals such as bears right down to much smaller animals such as foxes. Other innovations included monitoring the use of focal points where animals appear without having to rely on cameras that have limited range of view and collars that have limited battery life. These elaborations enabled the researchers to focus on long-range interactions between animals that can help to explain social interactions, co-presence, and events such as spread of disease.

Sometimes larger devices are replaced with chips that are embedded under the animal's skin for the purpose of tracking—a tactic that has been used for many years to ensure dogs can be found when they stray from their home.

5.9. Drones

Drones carrying sound recording, camera, video, heat detection, and other devices have reached a high level of sophistication for use by the military, and versions are now available in different sizes and shapes, from microversions made to look like dragonflies to much larger ones for monitoring a range of activities, from illegal logging in the Amazon rainforest to ivory poaching in Africa. Advantages of these devices are that many can cover large areas and they are small in size and make very little noise so they do not disturb wildlife.

The trade in wildlife and particularly ivory and rhino horns has reached epidemic levels. Using a combination of mathematical modeling and drones, Tom Snitch, University of Maryland visiting professor of advanced computer studies, predicts the movements of wildlife and then uses night-flying drones to watch for poachers (Kauffman, 2014; Snitch, 2015). Without the modeling component of his work, the area of surveillance would be too vast to police. The combination of collaborating with biologists who are experts in the animals' behavior, mathematicians who construct predictive mathematical models, and computer scientists and engineers to design, develop, and program the devices produces powerful devices for tracking and reporting animal behavior and poachers alike. Snitch comments that: "…the areas that you have to patrol are huge. You can't throw an unmanned aerial vehicle up into the night sky and expect to find something" (Kauffman, 2014). Predictive mathematical modeling enables researchers and wildlife biologists working in Kenya's Tsavo National Park and South Africa's Kruger National Park to locate areas where poaching may occur based on where rhino and elephant frequent. Having narrowed the scope of the search considerably, drones enable the park wardens to watch for poaching activity. Sometimes they locate poachers, but just knowing that there is a possibility of being detected is a powerful deterrent for them. However, despite success with this approach, there is apprehension from some governments about allowing the use of drones in their country, particularly when deployed by citizens from other countries, such as the United States, which has used them in combat situations.

The technologies discussed in this section present exciting possibilities for the future, but at present they are primarily in the hands of scientists who collaborate with computer scientists and technologists to design and develop the devices. As some of these technologies become easier to use, they will likely find their way into more citizen science projects, possibly through do-it-yourself Arduino-like development of sensing devices.

Key UX Issues and Questions Highlighted in The Discussion of Passive Data Collection Technologies

(1) Robustness and suitability for the study in which they will be used.
(2) Battery life, which is still a big issue, though one that is receiving attention from many scientists because it has implications for so much of our lives.
(3) Potential for an environmental impact associated with some of these devices that might disturb animal behavior and change ecology.
(4) Cost and expertise, often important issues related to data collection in citizen science, are especially so in large, complicated wildlife projects (e.g., assisting in whale or zebra migrations, helping to prevent poaching, etc.), which may mean volunteers' roles are limited to data analysis.
(5) Are there policies in place that could influence scientific work (e.g., as encountered by Tom Snitch's work on ivory poaching?)
(6) What services are available to capture data from sensors and make it available via the Internet or cloud services?
(7) How might smartphones and sensors be networked to address data collection and distribution in sparse sensor areas, perhaps involving citizen scientists? (O'Grady et al., 2016)
(8) How might the maker movement be encouraged to unite with citizen scientists to develop sensors that can be used in schools and local neighborhoods? Already small inexpensive lenses are being developed to use with smartphones for taking close-up pictures (see He, 2016, for a discussion of how these were used on a school fieldtrip). Arduino products also offer this potential (e.g., Norooz, Mauriello, Jorgenssen, McNally, and Froehlich (2015) for use of sensors for children to monitor their own heartbeats).

5.10. Considering the Role of Other Kinds of Technologies

Challenge is motivating for some participants, as has been mentioned already in the discussion about iNaturalist and iSpot. Furthermore, there is a huge market for games for all ages and some researchers are exploring the potential of games and gamified apps that contain a game-like component for motivating participation in citizen science projects. For example, Prestopnik and Crowston developed a gamified app called Happy Moths to identify moths based on characteristics of size, shape, color, and other morphological features (Prestopnik & Crowston, 2012). Adding game elements to an app, known as gamification, is also being explored by researchers, especially for attracting teens and young people. This approach is used in a citizen science app for plant phenology, called Floracaching (Bowser, 2016), discussed in the next section.

Virtual reality (VR) is featured in games, museum exhibits, and training activities, which will likely increase now that Goggle's Cardboard VR system is available (Figure 7a), possibly stimulating production of less expensive systems produced by Oculus Rift (Figure 7b) and others. VR enables participants who wear special headsets integrated with computer-programmed 3-dimensional worlds to feel immersed in those worlds. Google Cardboard provides a less immersive experience by enabling participants to view and move around in a virtual world after first loading an app onto their smartphone and then viewing the app via the Google Cardboard lenses.

It is conceivable that in the future, citizen scientists could film an organism (e.g., a bird) in its natural habit and view it in 3D, too. The additional environmental detail might promote deeper insights into the species' ecology that could lead to more accurate identification. VR has also been used for training in several fields, including surgery, so it may have a role in training citizen scientists for certain tasks such as water monitoring.

Experienced water monitoring experts report that training novices to be effective water monitors is complex for several reasons. Collecting measures of flow, pH, and other dissolved minerals is relatively easy as there are sensors to do that. In the United States, the tricky part involves using the Environmental Protection Agency (EPA) scales to subjectively describe the state of the stream in terms of amount of bank erosion, flow, and immersed fauna and flora (i.e., the epifaunal substrate). Typically, this part of the training is done indoors using slide presentations and then participants go outside and practice in local streams and rivers. But being trained indoors tends to be boring and participants frequently forget what they have been told when in a real outdoor situation, especially if they are distracted by rain and cold. VR is being explored as a promising aid for training participants in this subjective judgment component of water monitoring (Striner & Preece, 2016a; 2016b; Goldman & Preece, 2015). Guides such as Audubon's Creek Critter app (audubonnaturalist.org/index.php/conservation/creek-critters) are also used to identify the health of a stream through monitoring the presence of invertebrate stream creatures.

Figure 7. (a) Google cardboard (photo by Jennifer Preece), (b) Oculus Rift Headset (photo by Ben Shneiderman).

As other technologies are developed for citizen science projects, ensuring that HCI specialists are involved in the design process will help to make these projects successful.

6. Design

User-centered design describes design approaches that advocate focusing on users and placing their needs, behavior, likes, and dislikes at the center of design decision-making and practices (Preece, Rogers, & Sharpe, 2015). Participatory design (Kensing & Bloomberg, 1998; Schuler & Namioka, 1993) is an approach that encompasses an important category of design that involves collaboration between system users and system designers at the outset to create technologies that respond to users' needs and experiences. Research through design (Zimmerman, Forlizzi, & Evenson, 2007), collaborative research through design (Bowser, 2016), and crowdsourced design (Grace et al., 2014; Maher et al., 2014) are approaches that involve users in different ways.

This section discusses two projects: Floracaching, a gamified app for studying changes in plant growth from year to year—that is, phenology (Bowser, 2016), and NatureNet, a platform for collecting nature observations and design ideas to improve and tailor development of the system itself (Grace et al., 2014; Maher et al., 2014; Preece et al., 2014; Preece, Boston, Maher et al., 2016) that was developed using participatory design and crowdsourced design. Floracaching and NatureNet are both place-based systems that are anchored in particular places and have map interfaces.

6.1. Floracaching—Collaborative Research Through Design

Floracaching involves participants in looking for caches, plants in this context, and collecting data about the plant on a regular basis (Bowser, 2016). Participants can also develop their own floracaches for others to find. Floracaching is the plant phenology equivalent of geocaching, which is like a technology-supported treasure hunt.

Anne Bowser and her team developed a Floracaching app that focused on two key design issues: how to get more citizens engaged in botany and particularly, how to get new audiences, including younger people, involved. Phenology, the processes of recording seasonal changes in plants from year to year, is especially important in this period of climate change. Building on an already existing plant phenology project called Project Budburst (Henderson, Ward, Meymaris, Alaback, & Havens, 2012) (budburst.org) in which there was a loyal base of participants that fell within the demographic group of typical citizen scientists (mostly middle-aged, middle-income white women), the team wanted to build an app that was fun for younger people. Adding caching, which is like a treasure hunt but involves using cell phone apps, and gamification, seemed like an approach that might attract university students and other young people.

The gamified component of the design included a rating system with a leaderboard, similar to the one used in iNaturalist, for rewarding participants who found caches, contributed new caches, and helped others. This competitive element supported by in-game missions encourages participation. Floracaching also includes the ability to avoid the game features so that participants who are only interested in the citizen science task do not find themselves in competitive situations that they prefer to avoid.

In the gamified Floracaching app design project, intensive research through design was conducted with groups of participants from two U.S. universities: the University of Maryland, College Park, and Brigham Young University, Utah. Typically, research through design involves observation, interview, and interaction log data that are collected and analyzed holistically to answer a design question related to the system being developed. The design process is highly iterative and the results of this qualitative interpretation are fed back to the design team to inform the next instantiation of the design. While the researcher in this study observed the power of involving users in the process, she determined that the prototype designs that the users produced were more creative and that the users themselves enjoyed the process more when they worked together in pairs or small groups—an approach that she called collaborative research through design (CRtD), which she defined as "… an iterative process of cooperative design, where the collaborative vision of an ideal state becomes embedded in a design artifact" (Bowser, 2016, p. 2).

As in other types of HCI design, participants are involved in the design, but the depth of involvement is more intense

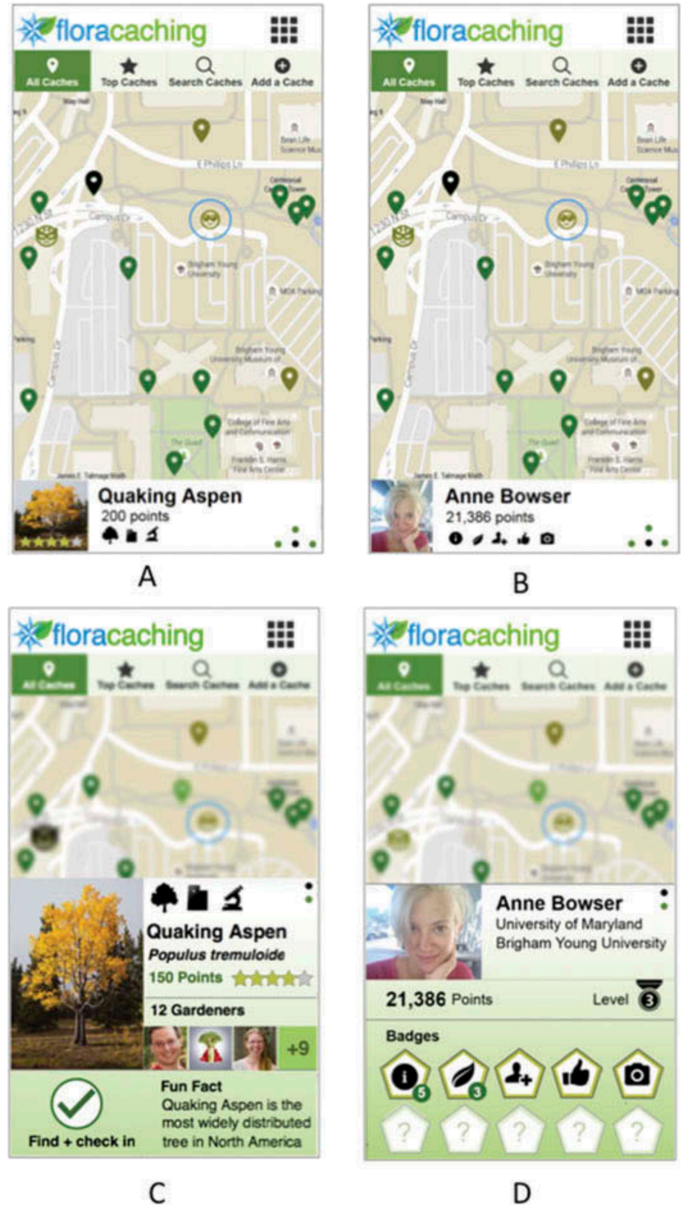


Figure 8. Screen shots of Floracaching: home screen with an expandable bottom container (A, B); plant profile page (C); player profile page (D). (Bowser, 2016, p. 159, Figure 13. p. 159). © Anne Bowser. Reproduced by permission of Anne Bowser. Permission to reuse must be obtained from the rightsholder.

and results in developing prototypes that are very close to what users really want. Bowser created this deep participant involvement by asking them to imagine and design for the primary purpose of Floracaching. Her participants responded to this charge by re-framing it from an app for phenology monitoring to an app that can be used to explore a local environment. In this way, Bowser went beyond user-centered and participatory design, which always asks people to design in a given context (not to re-imagine the context). The prototype of the system that evolved through this process contained detailed design ideas from the group that far exceeded initial expectations (Figure 8).

Achieving the level of involvement created in the Floracaching project is not without challenges. It takes a lot of time. The logistics of meetings have to be worked out, and how to appropriately incorporate the findings into the design of new prototypes. Perhaps most important of all, working relationships with the collaborative research through design team have to be developed, and building trust always takes time. However, this time is well spent as the final prototypes are ready for full implementation. In addition, there is a dedicated group of core users who feel ownership and who will encourage their friends to become users. Having this group of core users is a huge bonus as getting participation for a new citizen project is known to be difficult (Preece et al., 2016a; Silverton et al., 2015).

6.2. NatureNet—Crowdsourcing Design

Participatory design and research through design embody the same spirit of involving participants, which is a fundamental practice in HCI. However, even in participatory design, involvement of volunteers in the design process tends to be limited to certain times and is not continuous. The NatureNet team, comprised of partners from the universities of Colorado at Boulder, North Carolina at Charlotte, and Maryland at College Park, wanted to give volunteers more opportunities to influence the design of the NatureNet platform throughout the design process and after it was launched. One way of achieving this goal was by inviting volunteers to submit design ideas while they use the app to collect nature data. In other words, to crowdsource design ideas as well as collection of nature data. This approach is a form of metadesign that enables participants to express themselves (Fischer, 2011a) and take ownership of the technology.

The NatureNet platform encompasses three types of technology: (1) smartphone apps, used primarily for data input, (2) tabletop software to encourage participants to gather around and discuss their data, and (3) a website so that participants can still be involved after they leave the nature center and others who do not visit the particular nature centers but share related interests can also participate. This system architecture (Grace et al., 2014; Maher et al., 2014; Preece et al., 2014; Figure 9) is intended to support:

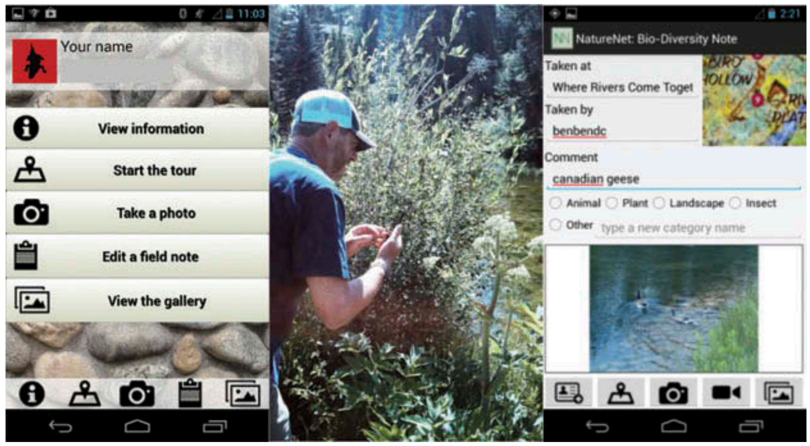
(1) core participants involved in projects at a nature center;
(2) casual participants who pass through the nature center or learn about the project from their core participant friends; and
(3) peripheral participants who discover the website from talking to friends or browsing the web (Clegg et al., 2016; Preece et al., 2016a; Figures 10 and 11)

The underpinning philosophy of crowdsourced design is openness: anyone can contribute, and it is considered important to consider and evaluate all ideas equally. As the system evolves, users typically gain opportunities and social rewards (Fischer, 2011a, 2011b; Fischer & Giaccardi, 2006) that empower them to continue to tailor the design to meet their own needs. Since a goal of many citizen science projects is to be scalable and to involve increasingly large numbers of diverse citizens, crowdsourcing design offers that potential and was therefore used as a starting point for developing the NatureNet platform (Grace et al., 2014; Maher et al., 2014; Preece et al., 2014). The hope was that diverse groups of problem solvers could outperform groups of experts by leveraging multiple viewpoints (Hong and Page (2004).

The research team hypothesized that participating in crowdsourcing the design of the UX in citizen science might increase engagement because people who have a stake in the design of the technology that they use may feel especially strongly committed to using that technology. Certainly in the Floracaching example, the students who committed so much time to collaborating on the project were very eager to continue to be involved in the project (Bowser, 2016). However, since collaborative research through design takes considerable time and organization, our team was eager to try to reduce design time while retaining participant involvement and commitment.

As a team, what we underestimated was that unlike other crowdsourced design projects that occurred in the business world with tech-savvy users, many of our citizen participants were not experienced in using technology. Furthermore, they were ephemeral visitors to the nature park in Colorado where we did our initial testing, and they had no long-term commitment to the project or the place. Our first round of testing produced fewer nature data and design ideas than we had hoped for (Preece, Boston, Maher et al., 2016). It became

Figure 9. NatureNet system architecture.



(a) (b) (c)

Figure 10. (a) Nature net mobile app, (b) data collection, (c) an observation.

apparent that being asked to contribute design ideas completely floored them. What is a design idea? What kinds of ideas were they expected to suggest? Our participants had no idea so most did not attempt to post anything.

After discussions with the naturalists from the nature center, and focus groups with some more experienced users, the team soon realized that we needed to scaffold the apps with more support for submitting both nature data and design ideas. In other words, we needed to realize that we were creating a learning platform (Clegg et al., 2016).

Later, this emphasis on designing for learning became particularly evident as we expanded our research to work with the Anacostia Watershed Society on sites spanning the District of Columbia and Maryland. Individuals participating in a training program for volunteer watershed stewards piloted mockups and later versions as they participated in a 12-week series of classes. The culmination of their class experience was to work either collaboratively or individually on a capstone project of the stewards' own choosing that would both contribute to watershed restoration and help educate their community. The types of projects selected included planting rain gardens for a school or church, planting trees to help absorb stormwater runoff, installing rain barrels to collect run-off, organizing stream clean-ups, etc.

Focus groups and interviews with the watershed stewards helped to guide the design of the next iteration of NatureNet. We collected their ideas in participatory design sessions in which ideas were written on sticky notes, clustered, and interpreted. The stewards were all familiar with Google's map interface and they wanted this same kind of map-based interface so that they could observe activities at other sites and zoom into their own location (Figure 11 and Figure 12). They also wanted information about resources to help with their projects. Other ideas that were suggested included providing information about where to go for project partners, where to get funding to buy project materials (e.g., rain barrels, food treats for participants), etc., as well as information about the watershed, nearby hiking trails, and its plant and animal life, and the ability to see previous projects to get ideas. They asked that NatureNet allow signup and login through other sites that they use such as Facebook, and that it should be easy to post to social media (where some already link to environmental organizations; see, for example, Cardoso, Warrick, Golbeck, & Preece, 2016), and they wanted to be able to "like" and comment on each other's data contributions and projects (Figure 13). In other words, they wanted many of the same features that are included in iNaturalist and iSpot and social media sites for promoting community. Creating community was a central theme of this stage in the NatureNet project.

(a)

Figure 11. (a) Early design for NatureNet tabletop. (b) Close-up of observation on tabletop.

(a)

(b)

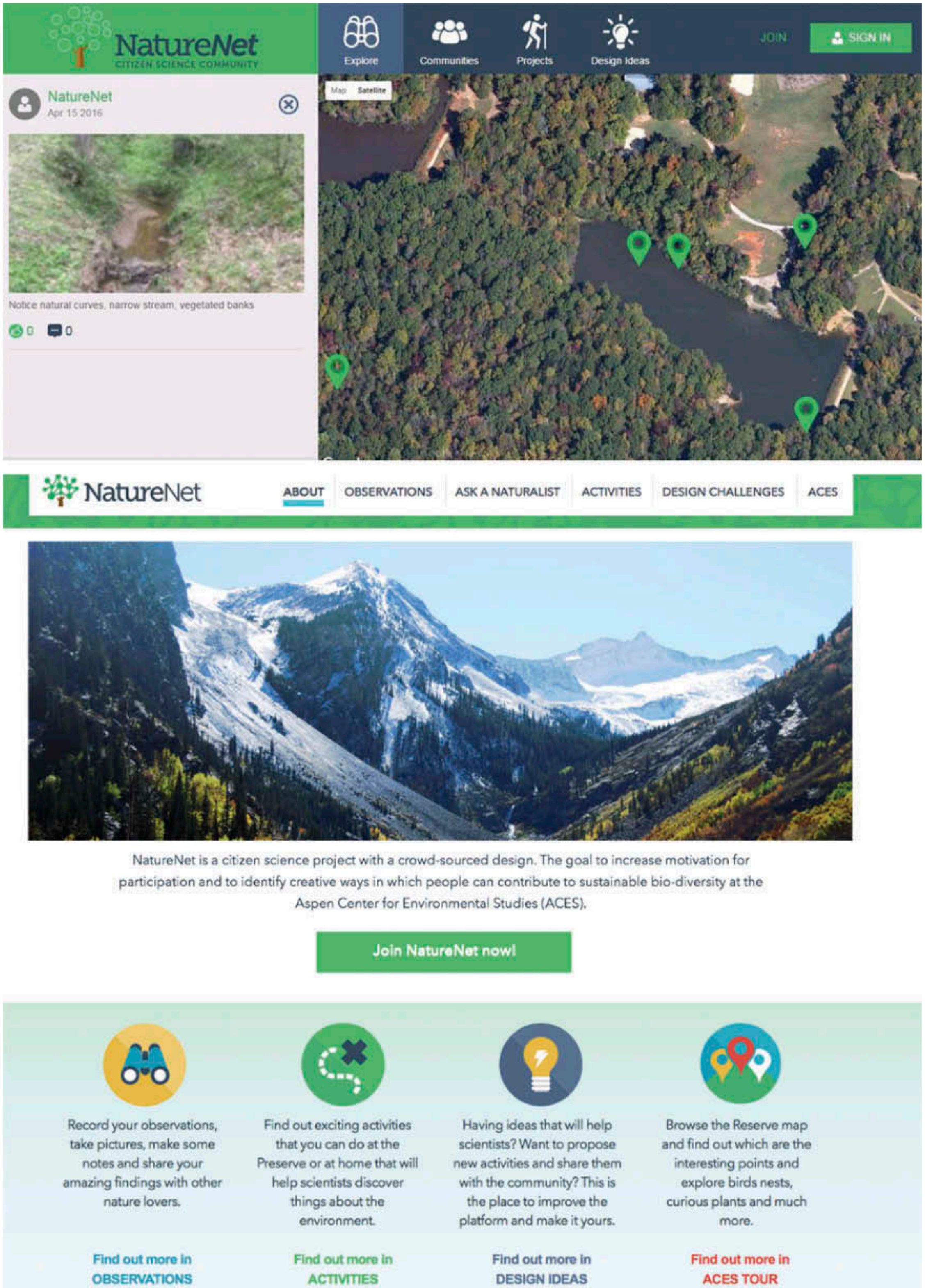


Figure 12. Later instantiations of NatureNet: (a) map view of the website, (b) the main features of the website.

Work with the Anacostia Watershed community and the Reedy Creek Nature Center in North Carolina impressed upon the team even more strongly that we needed to design to support diverse participants, not just in terms of age and gender but also ethnicity. The area around the Anacostia Watershed is home to many African-American and Hispanic community members, and Reedy Creek receives a wide variety of visitors who have immigrated from Mexico and Central and South America. But designing for a broader audience must go further than just language translation to also

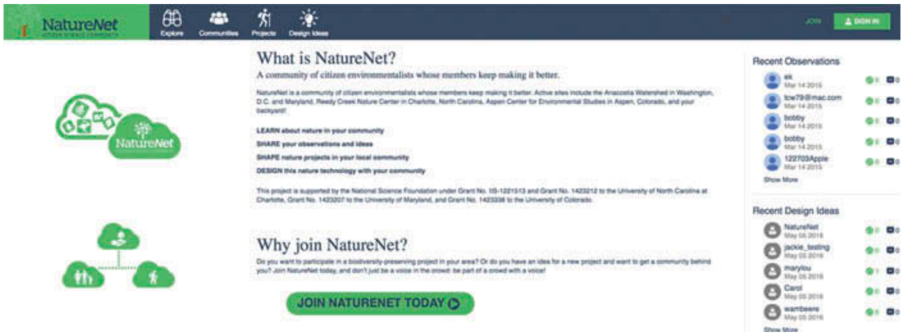


Figure 13. A later instantiation of the NatureNet website showing recent contributions of observations and design ideas with likes.

incorporate an understanding of how these different cultures are involved with and think about nature. For example, we heard from the naturalist at the Reedy Creek Nature Center that many people from Honduras, Mexico, and Nicaragua see the same warblers at Reedy Creek as they do in their native countries because these birds migrate annually between the two locations. However, they are given different names in different countries. Acknowledging these names is a first small step to more deeply engaging with immigrants from these countries.

6.3. Privacy

Ethical issues including privacy need to be considered when developing citizen technologies. These include checks that data submitted is genuine, prevention of malicious submissions and spam, tampering with data contributed by others, *ad hominen* attacks on co-contributors, and more. Privacy is especially important for projects that collect location data and personal profile information as mentioned previously (Bowser, Wiggins, Shanley, Preece, & Henderson, 2014).

Traditional science projects have well-established procedures for protecting participants' privacy and well-being. For example, research done in U.S. universities must comply with regulations based on The Belmont Report developed by the U.S. Department of Health & Human Services (1979). The Belmont Report proposes three fundamental principles that form the basis for standards such as Institutional Review Board (IRB) reviews. IRB approval must be obtained for research that involves humans and or personal data that could directly or indirectly be traced back to individuals. Research funded by the U.S. National Science Foundation, other funding bodies, and universities should not proceed without IRB approval, which may require several amendments and take several weeks to obtain. This important topic of privacy is worthy of whole papers, but for now, the three basic principles from the Belmont report can be summarized as follows:

(1) *Respect for persons* requires acknowledging a person's autonomy and the requirement to protect those with diminished autonomy;
(2) *Beneficence*, which involves two general rules: (i) do not harm another person and (ii) maximize possible benefits and minimize possible harms; and
(3) *Justice*, which is rather complex but basically it boils down to everyone should, according to their contribution, benefit equally and bear burdens equally. Five key issues are delineated: (i) to each person an equal share, (ii) to each person according to individual need, (iii) to each person according to individual effort, (iv) to each person according to societal contribution, and (v) to each person according to merit.

The Belmont Report provides guidance but does not specify exactly how that guidance is to be used in any particular situation. Policies and laws provide that information. For example, research done at American universities involving collection of human subjects' data can only be carried out if the subjects sign an informed consent form. This form has to specify the conditions under which the data will be collected and how it will be used and stored. Furthermore, the form must be reviewed and approved by an IRB Board prior to use. There are also specific laws that apply to particular individuals such as the Children's Online Privacy Protection Act (COPPA). COPPA prohibits collection of personal information from children under 13 years of age without permission from a parent or responsible adult such as a teacher. Similar laws and standards govern data privacy in the European Union where they tend to be applied more stringently (Bowser & Wiggins, 2015). Similarly, copyright protection, especially governing images, tends to be more rigorous in many countries outside of the United States.

Despite these protective measures, citizen science challenges existing scientific data collection and sharing processes and thus raises new and often unanticipated privacy concerns (Bowser et al., 2014). Projects that involve recording GPS locations where data is being collected, as many do, are of particular concern, particularly if the person is going to be at the same place regularly and there is a pattern of behavior that could be tracked. Similarly, as with most social media platforms, citizen science projects invite individuals to give personal data in their profiles and this personal data is then associated with data that they contribute. Many participants also volunteer information about themselves that could compromise their privacy. In this age of everyone being online, it is difficult and sometimes counterproductive for community building to limit personal exchanges, but policies detailing the potential dangers, as well as secure login procedures and data storage, are design issues that need to be addressed.

Another approach to improving privacy in citizen science projects could be achieved by engineering the system so that privacy is protected by the system's design without the user having to think about it. Cavoukian (2011) offers seven principles to guide designing for privacy in any system. "The Privacy by Design (PbD)" approach is characterized by proactive rather than reactive measures. It anticipates and prevents privacy-invasive events before they happen. PbD does not wait for privacy risks to materialize, nor does it offer remedies for resolving privacy infractions once they have occurred—it aims to prevent them from occurring. In short, "Privacy by Design comes before-the-fact, not after" (Cavoukian, 2011, p. 2). HCI specialists will recognize the similarity of this approach to the idea of "designing out usability errors" to prevent users from making certain well-known, annoying errors. There is also some evidence to suggest that individuals' attitudes toward privacy vary with context (Martin & Shilton, 2015). This could influence how citizens react to privacy concerns in different citizen science projects and how much attention designers need to pay to privacy. (For a concise overview of privacy in citizen science, see Bowser et al., 2014.)

Design is a huge topic in HCI and this article cannot do it justice. However, methods such as those discussed above can substantially contribute to the successful development of new citizen science apps and platforms. Some key issues to consider when designing for citizen science include:

(1) Deciding how best to involve citizen science participants in the design process.
(2) Managing deep involvement with participants that takes time and skill.
(3) Allowing participants to contribute creatively to all aspects of development and especially UX design.
(4) Scaffolding activities, especially for newcomers to both the topic and to using technology, to support learning and retention of participants.
(5) Taking care to use appropriate terminology, since terminology that may seem obvious to designers and scientists may be alien and confusing for citizen science participants.
(6) Understanding what is motivating or even just fun and for whom is important for different people. Some people love competition and leaderboards but not everybody.

In the end, it all comes down to making the effort to understand what citizen science participants really want! Citizen science leaders have much to gain from working with HCI specialists to design technology that citizens want to use.

7. Research Challenges

Before the mid-1990s, HCI research focused on micro HCI issues of consistency, error-trapping, menu and icon design, pointing devices, etc. By today's standards, these were "micro" usability concerns, which continue to be important, but increasingly, many designers take usability design for granted as something they must do. They understand that there are bigger, potentially paradigm-shifting "macro"-level HCI issues (Shneiderman et al., 2016), such as these: How to support community interaction across the world? How to do open-source software design for citizen science? How to scale up citizen science projects? How to develop tools and practices that can be adapted in culturally sensitive ways with leadership from people in developing countries? How to deal with different data standards in multinational projects? How to encourage data sharing across projects and countries? How to ensure the strengths of individual projects are leveraged while at the same time scaling up and combining projects that replicate activities? How best to facilitate scientists and volunteers working together? How to deal with privacy and security in this social media age? And, what is the next generation of citizen science projects going to be?

Addressing these issues has far-reaching consequences for HCI, biodiversity citizen science, and society at large. For HCI, this suggests an even stronger emphasis on qualitative methods such as case studies and ethnography. At the societal level, we need to ramp up how citizen science can contribute to preventing climate change, conserving biodiversity, educating the next generation, and fostering social justice. The five areas highlighted in Figure 1 provide five grand challenge areas as follows.

7.1. Communities

How Can We Motivate Long-Term Participation?

Work on motivation (Jennett et al., 2016; Nov, 2007; Raddick et al., 2010; Rotman, 2013, 2014a, 2014b; Rotman et al., 2012) has identified factors that initially draw people into different types of citizen science projects. More work is needed about how to convert these new users into people who return and keep contributing. What are the social network structures for different types of citizen science communities? How can we build trust, particularly between scientists and participants? Many people are looking to badging and leaderboards to reward participation. This works well for people who like challenge and competition, but do badging systems work for all users? Games and gamification are being explored, but what kinds of games/gamification are liked and by whom? How do these different design features impact people from different cultures?

How Can We Encourage Inclusion?

Broadening representation in citizen science is valuable because it ensures that multiple viewpoints and perspectives are presented (because we are all smarter together) and because lower income individuals and people of color (at least in the United States) are disproportionately affected by environmental degradation. Unfortunately, their neighborhoods tend to be the dumping grounds for industry, etc. and in the global context, the poor in underdeveloped countries will face the worst consequences of desertification, flooding, and food shortages to come, so bringing everyone to the table makes those conditions less possible to ignore.

Therefore, we must encourage more inclusion in citizen science. This means that those who are currently involved in citizen science have to work hard to understand how people of other ethnicities, cultures, and of other abilities think and feel about nature.

For example, in the face of drought conditions in parts of the United States, we need to think harder about agricultural and corporate use of water for such things as growing water-greedy crops like almonds, and siphoning off water for green lawns and golf courses in desert areas. Similarly, African countries where agricultural changes, compounded by cultural and population changes, face challenges about how to use water and manage natural resources. Research is needed about how indigenous people think about water and nature stewardship and how technology could be helpful.

Research is also needed to facilitate involvement by persons with disabilities who wish to participate in citizen science. For example, expert birders often recognize birds by their songs and calls. Similarly, people with sight problems often have heightened senses of hearing, smell, or touch. Michigan teacher, Donna Posont takes groups of young people with severe sight problems into nature to listen to birds and learn to identify them from the sounds they make (Posont, 2012). How else might citizen science projects engage people with disabilities?

What Makes Different Types of Citizen Science Communities Successful?

What makes communities successful in physical spaces, online, and in combinations of the two? We know that community issues concerned with a particular place are important in citizen science (Boston, Chetty, & Preece, 2015; Bowser, 2016; Chandler et al., 2012; Dickinson et al., 2010; Haywood, 2014; Haywood et al., 2016), There is also strong research on technology-supported learning communities, communities of practice (Wenger, 1999), online communities (Kraut et al., 2011; Preece, 2000; Preece, Nonnecke, & Andrews, 2004), communities of interest, and flexible spaces for informal science learning (Clegg et al., 2016; Gee, 2005). But we need to understand how communities form around citizen science, science education, conservation, and advocacy activities. Of course, often citizen science projects combine a number of these activities to greater or lesser extent. This may be due to leadership that promotes sub-communities. Understanding the dynamics and balance of different types of citizen activities needs to go beyond simple metrics (e.g., number of participants, number of data items), and to look for other quantitative and qualitative ways to evaluate projects in terms of long-term participants and their formal and informal learning outcomes.

Can We Develop Frameworks to Assist Understanding Community-Level Participation?

The reader-to-leader framework is based on understanding the usability and sociability required to support participants moving between different stages of participation in online communities (Preece & Shneiderman, 2009). We need frameworks that take a community-level perspective that help us to understand how citizen science communities evolve and form sub-communities. For example, a community-driven collaborative environmental project will likely be completely different from a community of individuals competing for the most badges for their contributions. It will also be important to identify which things tend to be generic across many communities and which are specific to a particular place and community's culture (Clegg et al., 2016).

What Kinds of Infrastructure are Needed for Different Types of Communities and Projects?

Bonney et al. (2009) propose a classification of different types of citizen science projects that was elaborated by Shirk et al. (2012). Research is needed to understand what types of technology infrastructure and social, organizational, and governance models work best for different types of citizen science projects at different stages of their development.

7.2. Data

What Is the Optimal Trade-off Between Promoting Participation and Ensuring Data Quality for Different Types of Projects?

Every citizen science project needs enough participants to function, and citizen science projects want to collect reliable data (Kelling, 2012) but is there a relationship between successful efforts to increase participation and the data quality of data these participants contribute?

What Kinds of Processes Help to Ensure Data Quality?

How do different ways of collecting biodiversity citizen science data, verifying data quality, and recording data provenance influence data quality?

What Is the Role of Trust in Sharing Data in Citizen Science?

Sharing data has been a dream in several areas of professional science for years, but there are barriers to doing so, including differences in data formats (i.e., standards), the time required to develop data sharing partnerships, etc. (He, 2016). But what is the role of trust required to share data both at the organizational and at the individual levels in citizen science projects with different infrastructures?

What Is the Relationship between Technology Infrastructure and Scaling Up Participant Involvement?

Sometimes projects can only scale when community infrastructures change. For example, when CoCoRaHS was a local project, project leaders interacted with volunteers directly. Now that the project is available in all 50 states in the United States, regional coordinators are required. eBird also had a similar experience.

What Would Encourage Collaborative Data Archiving across Different Projects and Aggregators?

There are several large aggregator sites for biodiversity data (e.g., Biodiversity Heritage Library (BHL) and EOL in the United States, and the UK Biological Records Centre). How much collaboration currently exists between these entities? What are the technical, human, and political issues that encourage or discourage deeper collaboration?

7.3. Technology

What Kinds of Technologies Are Most Appropriate for Which Kinds of People, Doing What Sorts of Tasks, in the Environments Where They Perform These Tasks?

This classic HCI question applies to many citizen science projects in which readymade technology is adopted, often provided in smartphones, or is developed based on best guesses about participants' needs.

Are There Particular Technologies That Work Better in Some Parts of the World and with Some Cultures Than Others? What Are the Characteristics of These Users and How Transferrable Is This Knowledge?

We know that smartphone charging centers exist in my countries where citizens take their phones to be recharged because they do not have access to electricity in their homes. Nigerian American journalist Dayo Olopade asks that the world reimagine Africa's challenges as opportunities to innovate in her book, *The Bright Continent* (Olopade, 2014). She points out that people in the United States tend to think that many processes in Africa are broken, which is a mistake as some things work well because people have devised other ways of achieving their goals at both community and individual levels. For example, the informal van transport system that is widely used in many parts of Africa appears chaotic but is usually highly coordinated by the drivers.

What Are the Design Challenges That Have to Be Overcome to Enable More Citizen Science Projects to Take Advantage of Drone and Tracking Devices?

Many passive data collection technologies are used primarily by scientists (e.g., long-term sensors) and hobbyists (e.g., drones). Is it just a matter of time before such devices can be produced cheaply enough to make their use viable in citizen science projects?

Battery Life or Alternative Energy Sources Are Significant Research Challenges for Collecting Data Using Most Technologies from Smartphones to Sensors to Drones. How and When Will This Situation Improve?

Research to further miniaturize technologies incorporated into smartphones, cameras, and drones and other new lightweight tracking technologies are particularly exciting areas for technical research.

Does VR Have a Role in Biodiversity Citizen Science?

VR is a popular topic, particularly since Google launched Google Cardboard mentioned earlier. With the cost of VR technology decreasing, what is its role in citizen science?

What Is the Role of Games and Gamification in Citizen Science?

Games and gamified apps are liked by some biodiversity citizen science participants—typically younger people. How might such systems be designed to be even more engaging and how might alternative UX design address the needs of those who are not interested in citizen science?

Can We Go Beyond Badges and Leaderboards? What Works and for Whom?

Badges and leaderboards generate enthusiasm for some participants but they are not for everyone. For example, research suggests that members of some minority groups are uncomfortable with overt competition and feel that they are being set up for failure when such an approach is emphasized. How can more cooperative approaches be designed for?

What Is the Best Way to Make Participants Aware of Privacy Concerns?

Increasingly, citizen science project leaders are becoming more aware of ethical and privacy concerns. How might HCI specialists be of assistance?

Can HCI Specialists Design Privacy Protection into Smartphones and Other Devices?

Perhaps Cavoukian's (2011) seven privacy standards offer a starting point. There are unobtrusive and more obtrusive ways this could be achieved. For example, photographs of faces could be blurred or automatically omitted unless the participant explicitly wants their face to be shown. Details of exact locations could be automatically withheld for a period of time if requested by the user. More obtrusive techniques include checking data that is reported to see if personal information is included and then asking the participant if they are aware that they are disclosing this information and whether they wish to proceed.

7.4. Design

Which Design Methods Broaden Inclusion?

Participatory design practices can pay dividends in achieving successful citizen science project infrastructure, though they are said to veer toward designing for elite groups rather than broadening the potential reach of citizen science to be more inclusive (Qaurooni, Ghazinejad, Kouper, & Ekbia, 2016). Research and collaborative research through design seem promising not just for achieving that goal but also for developing systems with participant buy-in (Bowser, 2016) but they take more time and resources than many projects can commit (Shneiderman, 2016). Crowdsourcing design has worked in corporations but how can we make it work better with diverse user populations? Are there other design approaches that more effectively include the full range of racial, cultural, and socioeconomic diversity in the world?

What Are the Benefits and Drawbacks of Collaborative Research Through Design and Crowdsourcing Design?

Is there a way to combine the two to capitalize on the benefits of each and reduce the drawbacks so that the sum exceeds that of the two parts?

How Can We Focus More on Macro HCI While Ensuring that Micro HCI Is Not Neglected?

This will involve developing new methods and adapting existing ones. Many microissues such as consistency could be checked automatically against a checklist. Macro HCI involves taking the broader context of use into account. Ensuring that designs are relevant for the context of use requires testing that is more case study-oriented and anthropological in nature.

How Can We Design Technology and Social Infrastructures That Support Scaling Up?
This will require techniques such as "collapsible scaffolding" that gradually become less prominent and adapts to larger and new populations of users. This includes ensuring that terminology feels familiar for those that use the systems. For example, terms that might be obvious to designers may be confusing and formidable to citizen science participants, particularly newcomers (Preece, Boston, Maher et al., 2016).

7.5. Save Our Species (SOS)—Doing Something Now!

E. O. Wilson told us in his 2007 TED talk, "My Wish: Build the Encyclopedia of Life," that we need to record life on earth so that we know more about the organisms that share planet earth with us and can take steps to ensure their survival (Wilson, 2007). More recently, E. O. Wilson commented that so far, though commendable, current projects and organizations working to conserve planet earth are not making progress fast enough (Wilson, 2016). Habitat loss and climate change is happening too fast and species are disappearing too rapidly. In areas in which habitat loss and climate change are most pronounced people are suffering. By documenting and making explicit the existence of new species, species loss, and redistribution of species due to habitat loss and climate change, we are supporting the cause for social justice for humans as well.

How Can HCI Specialists and Citizen Scientists Come Together to Respond to the Urgency of Saving Our Species?
Scaling up projects through cleverly designed technology that is usable, exciting, and emotionally satisfying for a diverse populations of participants across the world is a step in the right direction (Kobert, 2014; Vince, 2014; Wilson, 2016). Working collaboratively, HCI specialists, citizen scientists, and biologists have a major role to play particularly if partnerships are developed that impact government policy decision-makers.

How Can We Do More Together, Faster, and Better?
What will the next generation of citizen science projects be? This means developing technical systems to support scientists and citizens in collecting, analyzing, and archiving data, for example, the next generation of eBird, iNaturalist, iSpot, and Zooniverse. No doubt this is already being thought about but are the ideas inclusive and global and are politicians and funding agencies on board?

What Does Thinking Globally and Acting Locally Mean?
How should we reach out and support nations, cultures, communities, and individuals who are not yet involved in citizen science? What if project ownership and funding issues could be put aside and the best features could be used to develop a completely new global system with infrastructure to cope with different data structures, provenance, different language issues, etc.?

8. Conclusion

What overall conclusions can be drawn from this article? Citizen science is important for democratizing science and supporting formal science research. It is also exciting for citizens who are passionate about biodiversity and science. For HCI specialists, scientists, and citizens, there are so many opportunities to work together on important projects. HCI brings "technology design know-how." Scientists bring "scientific know-how" and environmental educators bring "education know-how." But most important of all, citizens bring diversity, energy, and passion!

Together, HCI specialists, scientists, conservationists, educators, and citizens can help to improve the lives of citizens across the world because, more often than not, striving to protect the environment is a form of social justice that benefits humans as well as the other creatures that live on planet earth. We all need clean air to breath, water to drink, food to eat, and a place to live. Working together, we can help to support science and educate people about nature. *The need is great and the time is now!*

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