The future of citizen science: emerging technologies and shifting paradigms

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Citizen science creates a nexus between science and education that, when coupled with emerging technologies, expands the frontiers of ecological research and public engagement. Using representative technologies and other examples, we examine the future of citizen science in terms of its research processes, program and participant cultures, and scientific communities. Future citizen-science projects will likely be influenced by sociocultural issues related to new technologies and will continue to face practical programmatic challenges. We foresee networked, open science and the use of online computer/video gaming as important tools to engage non-traditional audiences, and offer recommendations to help prepare project managers for impending challenges. A more formalized citizen-science enterprise, complete with networked organizations, associations, journals, and cyberinfrastructure, will advance scientific research, including ecology, and further public education.

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A bright, breezy morning greets Naomi as she and a team of 16 other volunteers embark on a wetland monitoring event in western Wisconsin. Naomi learned of the event through a social media site she follows. Within minutes after her arrival, she discovers and reports the location of a rare native sedge to SedgeNet – a national sedge database and citizen-science campaign – using her mobile phone. Her identification is instantly substantiated through image recognition and later corroborated by regional experts. Naomi's report is outside the predicted range of suitable habitat for the species and thus triggers a new species distribution model to be created, developed, and published. Meanwhile, Jose, an ecologist in California, discovers Naomi's report online, compiles the report with historical data, and refines his national plant species richness estimates, thereby creating an animated visualization of changes in species richness through time. Jose's animation attributes Naomi and other data providers and is automatically sent to all contributors. Theresa, a land manager for the Maine Department of Conservation, later uses Jose's animation to guide her agency's policy decisions related to statewide stream drainage activities, allowing her to recommend drainage sites that avoid locations likely to have high levels of species richness and biodiversity.

As the above vignette illustrates, the future of citizen science will likely be inextricably linked to emerging technologies. By spanning multiple spatial, temporal, and social scales, and by being designed to achieve a number of different outcomes, citizen-science projects will need to adopt new technologies to allow participants and organizers to communicate and interact effectively (Bonney *et al.* 2009a; Newman *et al.* 2011; Dickinson *et al.* 2012; Miller-Rushing *et al.* 2012; Shirk *et al.* 2012). As citizen science becomes more formalized and more widely accepted among scientific, educational, and community-oriented domains, additional factors – such as sociopolitical scenarios, economic conditions, and ethical considerations – will also influence how the field develops over time. Here, we discuss the future of citizen science (ie the process it uses to conduct scientific research, the culture of its future participants and programs, and the growing citizen-science community) using representative technologies and examples from the vignette above.

In a nutshell:

- Emerging technologies influence the scientific research process by streamlining data collection, improving data management, automating quality control, and expediting communication
- New technologies and skills (eg mobile applications, sensor networks, gaming) will appeal to a diverse set of citizen-science participants, but could potentially marginalize those unwilling or unable to adopt them
- A network of organizations (local, regional, and global) and professional associations, as well as open-access peer-reviewed journals and cyberinfrastructure support systems, will help organize the growing citizen-science community and provide future direction to the field

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Emerging technologies

New technologies, such as mobile applications (apps), wireless sensor networks, and online computer/video gaming, show great promise for advancing citizen science. Mobile apps involve software developed for use on portable devices such as smartphones and other mobile, web-enabled equipment. Wireless sensor networks consist of spatially distributed, autonomous or semi-autonomous sensors that monitor physical and/or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants. Gaming genres include alternate- and augmented-reality games, context-aware games, and games that involve social networking. Alternate-reality games permit multiple players to combine information and form coherent stories, and rely on peer-rated performance and feedback tied to location or place to solve real-world challenges (Kim *et al.* 2009). Collectively, these and other emerging technologies have the potential to engage broad audiences (Clery 2011), motivate volunteers (Cooper *et al.* 2010), improve data collection (Willett *et al.* 2010), control data quality (Kelling *et al.* 2009), corroborate model results (Darg *et al.* 2011), and increase the speed with which decisions can be made (Danielsen *et al.* 2010).

Figure 1. *Screen capture images of the Project BudBurst mobile application illustrating integrated tools to improve data collection and motivation. The mobile application automates capture of an observer's location, uses standardized plant lists and associated phenophase (periodic life-cycle event) definitions, provides data-entry forms for single reports, and offers a game ("Floracaching") to increase motivation for participants to return.*

The future of the citizen-science research process

The ways in which citizen scientists contribute to the scientific endeavor vary across projects. Some projects involve participants in a single step of the research process, whereas others involve participants in multiple ways (Danielsen *et al.* 2009; Dickinson *et al.* 2012; Miller-Rushing *et al.* 2012). Despite these differences, the typical research process for most citizen-science projects has been conceptualized as: gathering teams/resources/partners, defining research questions, collecting and managing data, analyzing and interpreting data, disseminating results, and evaluating program success and participant outcomes (Bonney *et al.* 2009a). We examine how each of these processes may change in the future.

Gathering teams/resources/partners

Innovative uses of existing technology may expedite team formation, improve the ability of program coordinators to locate professional scientists, help program coordinators to identify participants, and assist professional scientists and program coordinators with locating required resources. Existing databases – such as Citizen Science Central, SciStarter, and the Citizen Science Alliance – offer information about best practices, training materials, and searchable databases that help individuals find projects, resources, and partners. The expansion of these tools and continued advances in social media use will facilitate participant connections and provide opportunities for developing new projects based on freely available and scientifically vetted protocols and evaluation practices. For example, the event organizer in our vignette communicated with potential participants via social media, and volunteers used online social networks to validate data through mobile identification and reporting tools. Improved use of networked databases, social media, and cyberinfrastructure integrated into a more formal enterprise will enhance the organization of citizen-science-related information.

Defining research questions

Research questions can be formed through top-down (scientist-driven) or bottom-up (community-driven) processes (Danielsen *et al.* 2009). Current technologies stimulate creativity for both approaches. Participants may develop new questions aided by data visualization or scientists may see previously insurmountable challenges – such as geolocating place names, topographic features, and transportation networks – as achievable given a number of now-available "citizen sensors" (Goodchild 2007). The Zooniverse (www.zooniverse.org), a suite of scientist-driven projects, allows individuals to register, join one or more projects, and become de facto members of project teams (Clery 2011). Likewise, citsci.org (www.citsci.org) supports the formation of bottom-up and top-down projects on local, regional, or national scales, while also allowing for scientific discovery through meta-analyses of data integrated across different projects (Newman *et al.* 2011). Mobile apps and social media may provoke more creative discussion of research questions through real-time dialogue between scientists and citizens. For example, Naomi's sedge report in our vignette may prompt Jose to discuss the observed trend in species richness with a colleague who, in turn, asks questions about how that trend may correlate with climate change.

Collecting and managing data

New and existing technologies will improve the rate and quality of data collection through location-based, real-time mapping services (Lwin and Murayama 2011). For instance, Project BudBurst's mobile app (available at http://neoninc.org/budburst/gomobile.php) simplifies data

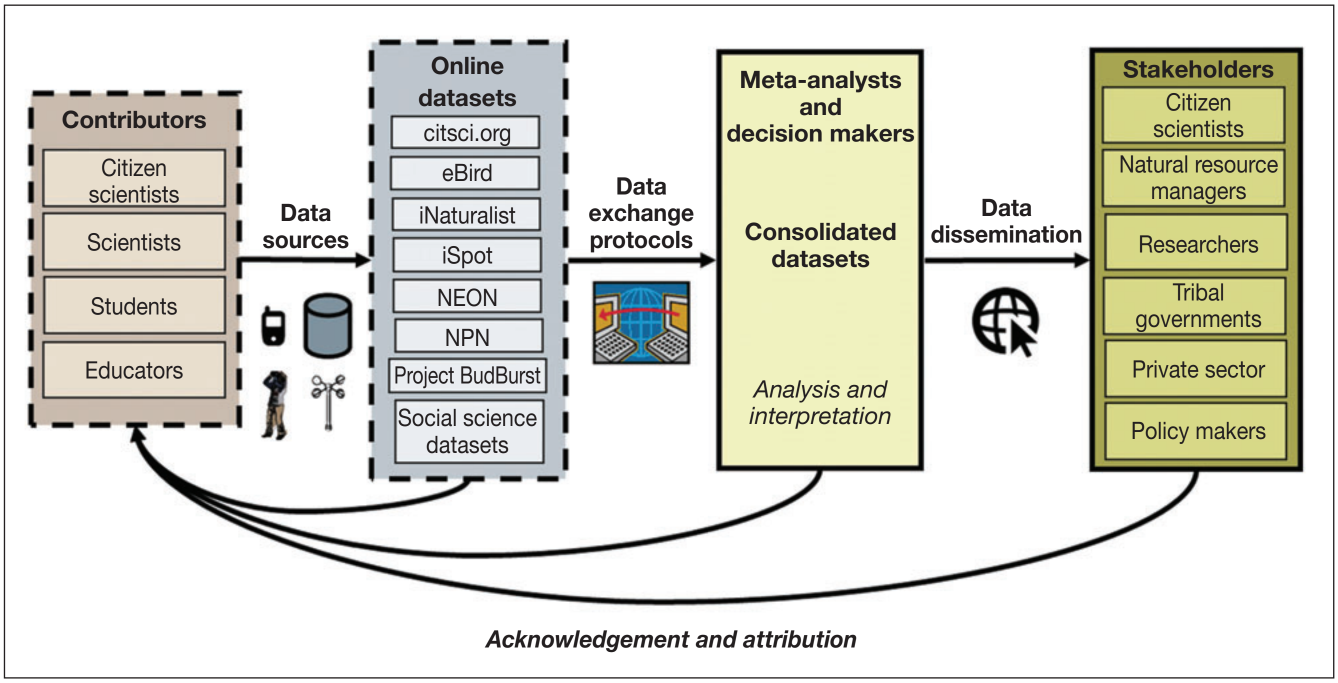

Figure 2. *Data contributed by various providers – such as citizen scientists, researchers, and graduate students – submitted to online data repositories (eg eBird, Zooniverse) make citizen-science data accessible. Increased investment in data exchange protocols, web service-based Application Programming Interfaces, and metadata documentation, such as the work being done by the Data Observation Network for Earth (DataONE), will increase the ability of scientists to re-use and re-purpose data. Results of analyses and visualizations performed through consolidated data that attribute contributors will increase the value of citizen-science datasets.*

collection by automating the capture of a participant's location (Figure 1; Graham *et al.* 2011). Additionally, wireless sensor networks enable chlorophyll and temperature profiling data to be automatically collected by automated monitors along lake transects (Cuff *et al.* 2008). Mobile phones are being transformed from communication tools to "networked mobile personal measurement instruments" (Wobbrock 2006; Paulos *et al.* 2008). Undoubtedly, tablet computers will operate faster and have greater functionality in the future, and as-yet-unimagined portable devices will be invented. Augmenting data collection with behavior- and context-aware alerts (eg location-aware alerts notifying data collectors that a given species observation is outside the normal range), for instance, is already occurring (Kim *et al.* 2009), and inexpensive "add-on" sensors that plug into mobile devices will likely become commonplace (Kuo *et al.* 2010). In the future, more ubiquitous computing will very likely occur (York and Pendharkar 2004), yet sensors will require calibration, data will need validation, and those collecting data will deserve proper attribution.

Although the continued use of mobile and networked devices seems inevitable, managing the volumes of data they generate will require improved data management capabilities (Figure 2). Increased use of web services will automate computer-to-computer interactions, metadata generation, tracking changes to data made over time, and data interoperability between databases. Geographic coverage will remain a challenge for continental-scale observations, particularly in sparsely populated areas, but these shortcomings may be addressed with advanced analytical methods (eg Kelling *et al.* 2009). The overall volume of data generated will lead to opportunities for data re-use and meta-analyses but may also present novel challenges related to "data deluge". Today's cyberinfrastructure investments in metadata, attribution, standardization, interoperability, and data curation and preservation will increase the value of citizen-science datasets, not only for scientific research but also for decision support, education, outreach, and improved scientific literacy.

Analyzing and interpreting data

Addressing the challenges posed by analyzing large-scale data will promote innovation in statistical analysis and modeling (Kelling *et al.* 2009). Grid and cloud computing will undoubtedly expand data storage and analytic capabilities, while improved browser-based visualization and analysis tools will allow participants to examine data more freely. In our vignette, for example, Jose's ability to integrate new reports with historical data and specify what to visualize (ie animated species richness changes through time) illustrates improved customization of analyses, where users can specify the data, along with independent and dependent variables, to be analyzed. Moreover, citizen scientists carrying mobile, networked, air-quality-monitoring devices could collect and interpret air-quality data as they walk around a given site (Willett *et al.* 2010); in such a scenario, participants might overlay these data with locations of known pollutant sources, thereby determining more precisely the spatial extent of environmental contamination (Cuff *et al.* 2008).

Disseminating results

The use of existing technologies (eg social networking) and the adoption of emerging technologies will enhance the ability of scientists and practitioners to centrally consolidate scientific information across projects, promote collaborative writing, and create virtual forums and communities (Hoffmann 2008; Waldrop 2008), thus increasing collective capital (Chiu *et al.* 2006; Chang and Chuang 2011). Automated feedback to participants about their data, how those data are used, and project results will become more accessible. As new information flows to interested audiences and feedback is received, knowledge sharing may advance well beyond what is currently possible. However, some of these same approaches may be more susceptible to bias and inaccuracies, making it important to distinguish scientifically valid information from opinion and/or advocacy (Grorud-Colvert *et al.* 2010). Well-designed "wiki" models that offer open peer-review forums may help to maintain data integrity (Hoffmann 2008). The success of such approaches is dependent on diverse stakeholder contributions, yet academic researchers currently neither are rewarded nor have any incentive to contribute to these types of projects. In the near future, such contributions will hopefully be as valued as publications in terms of advancing scientific careers; this would, for instance, benefit the experts who corroborated Naomi's report in our vignette.

Evaluating program success and participant impacts

Participants in citizen-science programs demonstrate greater scientific knowledge, skills, and positive attitudes toward science and the environment than the general public (Brossard *et al.* 2005; Bell *et al.* 2008; Bonney *et al.* 2009a). However, it is difficult to assess changes in multiple impact categories (eg attitudes, behavior) over the course of an individual's participation when such data are lacking (Crall *et al.* 2012). Adjustments in the way we collect social science data will also help to advance citizen science. Standardized and electronically available impact measures will enable comparisons across diverse projects. Allowing project managers to customize evaluations through standard measures will improve the ability to collect large volumes of quantitative data, while other tools, such as blogs, will continue to provide qualitative data. New technologies may ultimately provide more efficient ways to track individuals as they participate in a wide array of informal science education programs throughout their lifetime, while at the same time protecting participant privacy. Such improved tracking methods may reveal patterns in the ways that users collect data and provide a better understanding of user interests and skills over time, thereby advancing social science research.

■ What will future program and participant cultures look like?

Attributes of "successful" citizen-science programs include fostering long-term community-level involvement and activities, making use of appropriate cyberinfrastructure, developing diverse goals and evaluation strategies, engaging under-represented audiences, ensuring projects' financial stability, and effectively disseminating results (Bonney *et al.* 2009b). Emerging technologies will likely influence these and other aspects of the program and of participant culture, such as ethnic diversity and volunteer motivation and retention. We encourage managers of future programs to think critically about current technology adoption and to be open to experimenting with and exploiting new technologies as they emerge.

Diversity of participants

Emerging technologies will broaden participation in citizen science in ways that were not previously possible and, if used appropriately, will allow data collection by communities who traditionally remained uninvolved in scientific projects. For example, Worthington *et al.* (2012) described the Evolution MegaLab, where participants solicited from 15 European countries surveyed shell polymorphism in two species of banded snails, *Cepaea nemoralis* and *Cepaea hortensis*. Through the use of open-source software, a team of collaborators, and crowd-sourcing approaches, program materials – translated into 13 different languages – engaged 6461 people. Yet, diversifying participation remains an elusive goal for most projects. Despite their broader reach, new technologies may inadvertently create barriers that widen the "digital divide" between those adopting/having the technology and those avoiding/lacking it (Ess and Sudweeks 2001). Furthermore, different beliefs about how we advance science, what scientific methods ought to be used to improve our understanding, and how we share information across international boundaries may confound data sharing and data re-use, limiting long-term benefits (Pulsifer *et al.* 2011). As citizen-science programs adopt new technologies, sensitivity to social, cultural, economic, and political factors will be critical to the success of projects that cross boundaries and involve local/traditional ecological knowledge (Ballard *et al.* 2008).

The motivation and retention of volunteers

Participants are motivated by contributing to authentic scientific research, by the social interactions such participation affords (Van Den Berg *et al.* 2009), and, in online-gaming contexts, apparently by competition and symbolic rewards, such as badges (Cooper *et al.* 2010; Clery 2011; Darg *et al.* 2011). Award systems use competition as

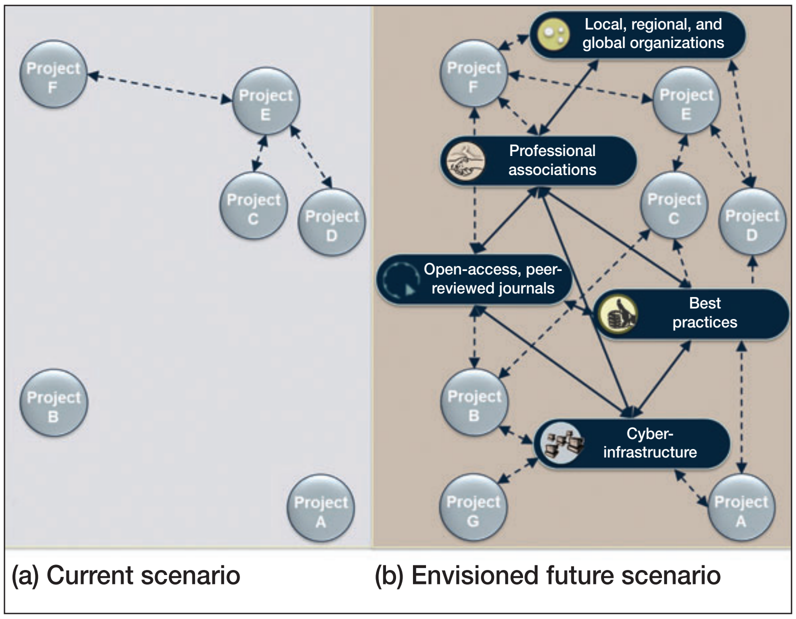

Figure 3. *(a) Existing citizen-science enterprise where some projects interact and learn from each other and some may not. (b) The same scenario shown in (a) augmented with five new elements of a more formalized citizen-science enterprise, including: local, regional, and global organizations; professional associations; open-access, peer-reviewed journals; resources for best practices; and expanded cyberinfrastructure support systems. The future shown in (b) will be poised to better support the myriad existing and future projects (such as the new project labeled "Project G") that span multiple spatial, temporal, and social scales, and that focus on diverse subjects.*

motivation, pitting teams against teams and individuals against individuals, as in the popular online Fold-It game (Cooper *et al.* 2010; Graham *et al.* 2011). Enjoyment is an intrinsic underlying motive for participation (Nov *et al.* 2011). As teams of scientists and volunteers form, they learn from and become motivated through their collective capital. Gaming and a sense of camaraderie make scientific exploration and discovery enjoyable; the potential influence of gaming on participant motivation shows the importance of incorporating recreation into citizen science. In one likely outcome based on our vignette, Naomi and the team of volunteers take pride in contributing to science and may even count their reports through time, comparing their "score" to those of other teams conducting similar monitoring.

Panel 1. Recommendations for projects

- Choose appropriate technology for your participants
- Evaluate new technologies with make-versus-buy and cost–benefit analyses, paying particular attention to reliability
- Adopt well-established, well-documented, and well-supported technologies
- Consider interoperable, customizable, open-source solutions where possible
- Follow best practices and use standardized data-collection and data-management protocols where available

Technology adoption/appropriateness/preparedness

The speed at which new technologies will emerge within scientific and citizen-science communities will be largely dependent on widespread adoption (Rogers 2003). Trends indicate that volunteers are more willing to adopt (and even to share their geographic location using) technology than ever before (Krumm 2009). Programs in the future will thus represent unique assemblages of yet-to-be-determined technologies, people, and sociocultural situations (Cuff *et al.* 2008). Given such uncertainty, we recommend some guidelines for citizen-science projects (Panel 1).

Paradigm shifts and what they may hold

The future of citizen science will be affected by, among other factors, networked and open science and the use of gaming to encourage participation by younger and more ethnically diverse participants. Networked and open science is transforming how scientific discoveries are made (Nielsen 2012). Where traditional citizen-science projects may have included field trips to collect water-quality data or plant and animal observations, new projects involving "continental-scale science", mobile and web-based activities, and large-scale data visualizations and analyses will reach broad audiences. After-school programs for urban youth might offer citizen-science-oriented video games. Tablet computers might become more widely available in some of the remote corners of the world, allowing villagers to record variations in wildlife populations. More ubiquitous computing will create a population of data-aware, always-connected citizens, allowing people to collect data and contribute to science asynchronously. The concept of citizen science itself could become blurred as data collection tied to games and linked to social interaction becomes an integrated part of daily life.

Citizen science as an evolving discipline and community of practice

To advance science and education, we argue that expanded efforts are needed to garner support for and recognition of citizen science as a discipline and an important form of volunteer service (Figure 3). Such an enterprise could consist of local, regional, national, and international organizations, professional associations, and peer-reviewed journals that organize and support practitioners, scientists, and other stakeholders. This could be accomplished through the creation of a dedicated professional association that disseminates

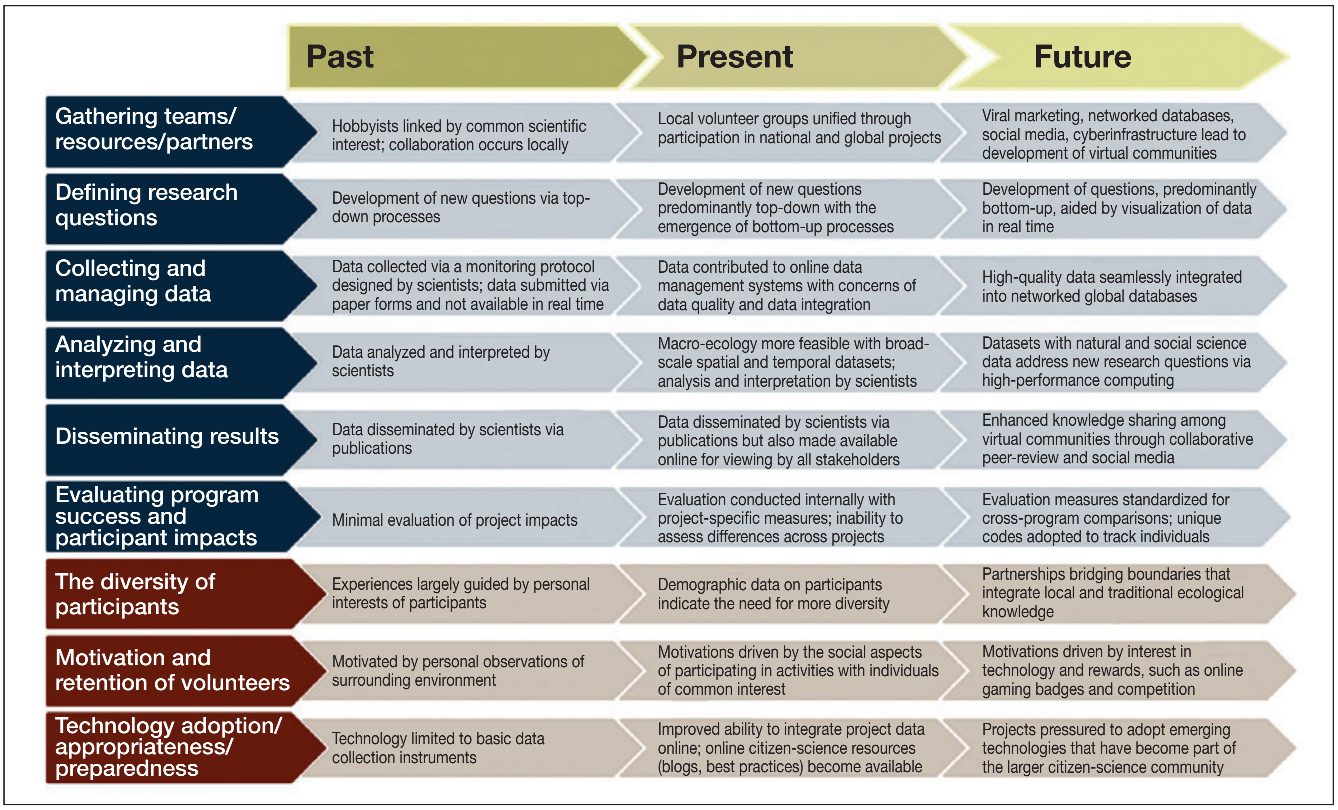

Figure 4. *A summary diagram illustrating key research process steps typically followed by citizen-science programs (first six blue trajectories) and aspects of program/participant cultures as seen in the past (Miller-Rushing* et al. *2012), present (Dickinson* et al. *2012), and future.*

advances in the field through annual meetings, encourages open dialogue, publishes an open-access peer-reviewed journal centralizing associated literature, and generally serves to guide the field. A "network of data networks" and regional "citizen-science centers" could also maintain interconnected databases listing programs, best practices, standardized protocols, and vetted training materials; deliver cyberinfrastructure support for data management; offer complex analysis and visualization tools; and provide forums for theoretical, empirical, and technological advances (Figure 3). Taken together, these efforts would advance the citizen-science research process, as well as citizen-science programs and participant cultures through adaptive management practices (Figure 4). We recommend a few guiding principles for the emerging community of practice as it advances (Panel 2).

Panel 2. Recommendations for the emerging field of citizen science

- Embrace both centralized national programs and decentralized local efforts
- Encourage creative enthusiasm to increase likelihood of success of citizen-science projects at large and small spatial and temporal scales
- Encourage use of open-data standards and open-source software (code that is free to use and can be changed by others to advance the code base)
- Seek broad and diverse participation through local and traditional ecological knowledge
- Maintain a cooperative and supportive environment for all programs, practitioners, and participants, realizing the value of each to the advancement of the field

What does the future of citizen science hold?

Citizen-science projects and activities will rely on standardized field protocols to collect and visualize data necessary to monitor socioecological systems at multiple spatial and temporal scales. Citizen-science projects may evolve to address both local issues and grand societal challenges. Wireless sensor networks may connect the laboratory to the natural environment, shifting the focus from elite science to a reality where data collection, analysis, and interpretation are performed by everyday citizens going about their daily lives *in partnership with* professional scientists. A daily bicycle commute could automate air-quality monitoring; gardens could become networked micro-environment monitoring stations; data integration, visualization, and analyses could no longer require difficult file-format conversions; and scientists could more easily integrate continental-scale citizen-science datasets with professional datasets that are augmented by locally relevant citizen observations.

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