The current state of citizen science as a tool for ecological research and public engagement

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Approaches to citizen science – an indispensable means of combining ecological research with environmental education and natural history observation – range from community-based monitoring to the use of the internet to "crowd-source" various scientific tasks, from data collection to discovery. With new tools and mechanisms for engaging learners, citizen science pushes the envelope of what ecologists can achieve, both in expanding the potential for spatial ecology research and in supplementing existing, but localized, research programs. The primary impacts of citizen science are seen in biological studies of global climate change, including analyses of phenology, landscape ecology, and macro-ecology, as well as in subdisciplines focused on species (rare and invasive), disease, populations, communities, and ecosystems. Citizen science and the resulting ecological data can be viewed as a public good that is generated through increasingly collaborative tools and resources, while supporting public participation in science and Earth stewardship.

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Citizen science engages non-professionals in authentic scientific research, ranging from long-standing, large-scale projects like the Breeding Bird Survey to the more personalized research experiences offered by the Earthwatch Institute (WebTable 1). The combination of historical data and assembly of a large, dispersed team of observers creates opportunities for ecological research at unprecedented spatial and temporal scales. Many ecologically based citizen-science projects collect important baseline data, which positions them to respond to crises such as the 2010 *Deepwater Horizon* oil spill in the Gulf of Mexico (Sullivan *et al.* 2010). Other projects routinely monitor mortality in a particular population or species, helping to identify threats to native species and to people (eg Coastal Observation and Seabird Survey Team [COASST] and Road Watch in the Pass; WebTable 1). Dispersed data collection and the ability to collect observations and connect with people, in places, and at scales that would otherwise not be possible, render citizen science increasingly important to environmental research (Dickinson *et al.* 2010; Dickinson and Bonney 2012).

In a nutshell:

- Citizen-science projects guide public participation in a breadth of ecological research topics and studies of abiotic factors
- In combining research with public education, citizen science also addresses broader societal impacts in a profound way by engaging members of the public in authentic research experiences at various stages in the scientific process and using modern communications tools to recruit and retain participants
- Over the past 20 years, several new developments in information science – especially in data informatics, graphical user interfaces, and geographic information system-based web applications, which can now be ported to smartphones and other hand-held devices – have been vital to the emergence of citizen science
- Citizen-science projects face issues of prioritization and sustainability, raising the question of how government funding and partnerships might help sustain public interest in doing science for society

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Today, the internet and geographic information system- (GIS-) enabled web applications allow participants to collect large volumes of location-based ecological data and submit them electronically to centralized databases. The ubiquity of smartphones, the potential for digital photo validation of questionable observations (eg COASST; WebTable 1), and the development of infrastructure for creating simple online data-entry systems (eg www.citsci.org; Table 1) provide added potential for initiating projects quickly, inexpensively, and with stringent criteria to ensure data accuracy. These same web-based tools are democratizing project development, allowing for the creation of data-entry systems for community-based projects that arise out of local, practical issues or needs (eg Extreme Citizen Science; WebTable 1). Although we cannot currently assess the impact of this democratization for ecological research, such empowerment means that resource management decisions, and the data that drive them, are more likely to be in the hands of the people who will be affected by the outcomes.

Currently, the contributory model of citizen science has been the most productive in generating peer-reviewed publications in the field of ecology, whereas collaborative and co-created approaches often have other, more practical

Table 1. A selection of projects and websites active in 2012 that provide cyberinfrastructure, tools, and information for project developers and participants

Websites	*Description*	*Resources*
Citizen Science Central www.citizenscience.org	Provides support and aggregates resources for project developers, participants, practitioners, educators, researchers, information technology specialists, and evaluators	Toolkit for project development, tips and tools, reference database, conference proceedings, searchable project list, discussion forum, news feed, professional network
CitSci.org www.citsci.org	Supports the cyberinfrastructure and data management needs of citizen-science projects in a way that allows many users to create their own interface	Tools for creating customized data-entry forms so that volunteers can submit data
Data Observation Network for Earth www.dataone.org	Offers cyberinfrastructure and management structure to ensure preservation and access to multi-scale, multi-discipline, and multi-national science data, including citizen-science data	Educational tools on data management and National Science Foundation data plan requirements, data standards that will enable the integration of data from diverse studies and taxa, data analysis and visualization tools
The Public Laboratory for Open Technology and Science www.publiclaboratory.org	Represents an online community that develops and applies open-source tools to environmental exploration, providing participants with inexpensive and accessible "do-it-yourself" tools and techniques	Tools and methods, information on conferences
SciStarter www.scistarter.com	Aggregates information, videos, and blogs about citizen-science projects; allows researchers access to "community of doers" through targeted marketing of participation opportunities	Project finder and add project tools, editor's picks, member and site blogs
Volunteer Water Quality Monitoring www.uwex.edu/ces/csreesvolmon/	Supports expansion and increases in the capacity of existing Extension Volunteer Monitoring Network; supports development of new programs	Aggregates information and support materials for water-quality monitoring across the US

goals (Bonney *et al.* 2009a; Dickinson 2010; Miller-Rushing *et al.* 2012). On the other hand, several bodies of theory suggest that the impacts of collaborative and co-created projects have the potential to extend beyond what some ecologists envision. In particular, research on collective intelligence indicates that diversity matters and that new leaps of logic, innovation, and invention are more likely to arise when people of different backgrounds and abilities work together toward a common goal (Woolley *et al.* 2010).

Whether contributory, collaborative, or co-created, ecologically based citizen-science projects are a natural fit for scientific endeavors with important environmental or public-policy implications because they engage the affected populations from the start. Built upon the assumption that participation in scientific research creates authentic learning experiences, citizen science is also a powerful way to generate ecological knowledge, inquiry, and place-based nature experiences for the public (Figure 1). Because of its participatory nature, citizen science appears well suited to elevating public understanding of and support for science, the environment, and Earth stewardship (Dickinson and Bonney 2012; Shirk *et al.* 2012). Of course, benefits to professionals and participants overlap because learning, data, and results constitute a fully sharable public good (Triezenberg *et al.* 2012).

Here, we summarize how citizen science contributes to the field of ecology, focusing on the value of engaging non-professionals in ecological research. How have ecologists strengthened their research programs by working with members of the public? What are the broader impacts of these burgeoning cross-disciplinary endeavors that encompass the human and natural dimensions of environmental change? And what do ecologists need to know to become involved?

The use of citizen science by professional ecologists

Citizen science's importance to the science of ecology lies in what ecologists can do with citizen science that they could not do without it. In the following sections, we briefly review the ways in which citizen science makes distinctive contributions to ecology.

Landscape ecology, macro-ecology, and climate change

Geospatial technologies have supported a vast and growing effort to understand large-scale patterns of change in the distribution, abundance, and presence of organisms across time and space (Dickinson *et al.* 2010). Advances in these technologies have coincided with substantial growth in the fields of landscape and macro-ecology. Landscape ecology practitioners ask how the composition of surrounding landscapes influences which, and how many, organisms live there, or how well they survive and reproduce. Macro-ecology, on the other hand, is concerned with underlying processes, such as how body size, species interactions, and abundance determine the ranges and distributions of organisms along landscape, latitudinal, and climatic gradients. Both of these relatively new subdisciplines are supported by the availability of GIS-enabled land-cover data; geospatial data on abiotic factors, such as weather, water quality, and atmospheric pollution; and data on the distribution and abundance of organisms – all collected at large geographic scales. While some data can be obtained with satellite images and other remote-sensing technologies, others can be acquired only through the involvement of massive research teams like those assembled by citizen science. Examples include the presence, abundance, and demography of organisms (eg eBird, Monarch Larva Monitoring Project) as well as more fine-scaled and thus ecologically relevant measures of water quality, weather, and light pollution (eg Streamwatch, Community Collaborative Rain, Hail, and Snow Network [CoCoRaHS], GLOBE at Night; WebTable 1).

Citizen science has detected climate-change-induced range shifts in a diversity of organisms (Parmesan and Yohe 1993; Root *et al.* 2003), phenological and elevational shifts in flowering times of plants (Miller-Rushing and Primack 2008; Crimmins *et al.* 2009), and advances in the egg-laying dates of migratory birds (Dunn and Winkler 1999). Increased interest in understanding how climate change may influence community structure and ecosystem function (eg via climate forcing) lends new urgency to the gathering of large-geographic-scale data and places a premium on digitizing older records to understand biotic changes that have already occurred (eg The North American Bird Phenology Program, www.pwrc.usgs.gov/bpp/Research2.cfm; historical lilac and honeysuckle databases, see Schwartz *et al.* 2012).

Ecology in the Anthropocene: urban, agricultural, and residential ecology

The term "Anthropocene" was put forth to capture the idea that direct human impacts are having so large an effect on ecosystems around the globe that we have effectively entered a new geological era (Crutzen 2002). Researchers have begun to emphasize the importance of understanding the ecology of working landscapes and the enactment of conservation measures within anthropogenic biomes or "anthromes" (Ellis and Ramankutty 2008). Citizen science is ideal for working with farmers and residents to study the ecology of urban, agricultural, and residential landscapes (Figure 2; Cooper *et al.* 2007; Ryder *et al.* 2010). For example, studies of garden habitat in suburban Tasmania, Australia, showed that household gardening practices can play an important role in bird conservation (Daniels and Kirkpatrick 2006), whereas the Neighborhood Nestwatch project in Washington, DC, demonstrated increased nest predation and reduced nesting success of birds at the urban end of the urban-to-rural gradient (WebTable 1; Ryder *et al.* 2010). By being poised to gather data on social landscapes as predictors of biodiversity, citizen science provides a framework for studying coupled human and natural systems (Field *et al.* 2003). Citizen science may be a particularly good match for research programs on urban Long Term Ecological Research Sites (www.lternet.edu/sites/), which have begun to include social inputs as explanatory variables in the analysis of ecosystem dynamics.

Figure 1. *Citizen scientists at work in the field.*

Finding rare organisms, tracking movement, and detecting species declines

Citizen science, with its "many eyes", is an effective way to find rare organisms, track invasions, and detect boom-and-bust events, such as irrupting bird populations (Hochachka *et al.* 1999). It has been used to find a ladybug species thought to have gone extinct (WebTable 1, The Lost Ladybug Project; Losey *et al.* 2007), track the spread of the newly emerged house finch eye disease caused by the *Mycoplasma gallisepticum* bacterium (Dhondt *et al.* 1998), and detect the arrival and distribution of invasive plant species in Texas (Gallo and Waitt 2011). Citizen science can also be used to track migrations, as with the Monarch Larva Monitoring Project (WebTable 1), that demonstrated "migratory culling", in which *Danaus plexippus* adults that successfully migrated had reduced disease prevalence and levels of parasitism (Bartel *et al.* 2011). It is useful for monitoring declines, as evidenced by the Reef Environmental Education Foundation, which recruited scuba divers to conduct more than 83 000 surveys documenting declines in 14 shark species over a 15-year period (WebTable 1; Ward-Page *et al.* 2010). Citizen science is especially powerful

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***Figure 2.** For the first time, human impacts have pushed the Earth into what is effectively a new geological era, the Anthropocene, which also means that Earth stewardship is more important than ever.*

when combined with conservation goals. For example, a research initiative (Grupo Tortuguero) co-created with local fishermen in Mexico identified bycatch of small-scale local fisheries as an important conservation threat to loggerhead sea turtles (*Caretta caretta*), through a partnership with the very communities whose practices could make a difference (WebTable 1; Peckham *et al.* 2007).

Use of citizen science to augment traditional research programs

A prime example of applying citizen science as a tool to augment traditional research methods is the engagement of local residents and Girl Scouts by the Cary Institute of Ecosystem Studies to help distribute 270 525 acorns (1172 kg) on three experimental plots. This experiment was intentionally conducted in a "bust" year, when acorn production was so low that supplementation would make a substantial difference in the number of acorns present on control versus experimental plots. The result was an important paper, published in *Science*, describing the complex chain of ecological interactions that underlie the frequency of human exposure to Lyme disease (Jones *et al.* 1998). In this chain of interactions, gypsy moths (*Lymantria dispar*, oak defoliators) reduce acorn production, which influences white-footed mouse (*Peromyscus leucopus*), deer, and infected tick densities, and ultimately the exposure of humans to infected ticks.

Layering question-driven research onto existing monitoring projects

Existing monitoring projects can be used to launch question-driven studies. In a study of geographic variation in burr oak (*Quercus macrocarpa*) acorn size, Project FeederWatch (www.FeederWatch.org) participants, who submit bird counts at feeders, were recruited to mail five acorns collected from each of five trees at sites spanning from Michigan to Texas. The results of this study suggested that the geographic variation in the size of burr oak acorns, which are large in the south and small in the north, is due to environmental effects on growth and not to a preferential tendency of dispersing birds to carry smaller acorns northward (Koenig *et al.* 2009).

As with any field observation, patterns observed through citizen-science-acquired data often elicit questions that require the development of new targeted protocols. In one study, 200 highly engaged citizen scientists were recruited from the Birds in Forested Landscapes (www.birds.cornell.edu/bfl/) participant base to sample calcium- (Ca-) rich invertebrates, in testing the hypothesis that wood thrush (*Hylocichla mustelina*) declines in areas with high levels of acid precipitation were ultimately caused by Ca deficiency. The results showed an association between acid deposition and reduced trophic Ca available for egg production, and were published in the *Proceedings of the National Academy of Sciences* (Hames *et al.* 2002). This example reflects ways in which ecologists can recruit a subset of "super citizen scientists" to conduct question-driven research through the use of specialized protocols.

Statistical innovations arising from the challenges of working with large, heterogeneous datasets

Citizen science presents analysis-related challenges (eg sampling bias, observer variability, and detection probability) that are not easily addressed with statistical hypothesis testing or model selection approaches (Weir *et al.* 2005). Recently, citizen-science research has tapped into new computational approaches for analysis of large, complex datasets (Kelling *et al.* 2009). As in other fields, these approaches are revolutionizing the ways in which ecologists analyze large-scale patterns and visualize change at large geographic scales (Figure 3).

Attribution of credit and authorship

In the field of ecology, citizen-science participants are rarely included as authors of peer-reviewed publications unless their efforts go beyond following a protocol and submitting data. Although it makes sense, at the very least, to extend recognition to both the citizen-science participants and the institution delivering the project in the acknowledgements section of an associated manuscript, this has not become standard practice. There is a need for citizen science to adopt the model being widely considered across disciplines, in which all participants for a given paper are acknowledged and their explicit roles described (Venkatraman 2010).

Dovetailing research with conservation and management

As citizen science continues to facilitate a variety of large-scale ecological studies (Dickinson *et al.* 2010), it supports the work of conservation partners by providing information relevant to ecological management at the level of communities and across state and national boundaries (eg the US State of the Birds Report [www.stateofthe birds.org/] and the US–Mexican partnership aVerAves [www.conabio.gob.mx/averaves/]). One of the strengths of citizen-science research is its potential to address conservation problems across entire ranges of species.

Citizen science as a means of achieving broader impacts of ecological research

Many citizen-science projects have received funding because of their ability to connect authentic scientific research with science education. A critical component of this effort is the creation of educational materials, including background information that allows participants to understand the theory and ideas behind the research, a comprehensible description of the research questions, and clearly described, tested protocols for how to carry out observations. For all project types, the potential educational benefits range from acquiring skills needed to collect data accurately to critical scientific thinking and inquiry, in which participants apply knowledge to generate new questions and then design studies or develop models to answer those questions. Many projects strive to support participants' use of critical thinking skills in their everyday lives and their use of science in relevant contexts, such as Earth stewardship and scientifically informed decision making. Achieving specific learning outcomes does require explicitly articulated goals and attentively designed project activities (Jordan *et al.* 2011).

Levels of interaction and mechanisms of contact between professionals and participants differ among projects, and may influence participant experiences and learning. Large-scale projects like Project BudBurst (www.budburst.org), the Great Sunflower Project (www.great sunflower.org), and Project FeederWatch rely mainly on web content, email, telephone, and the US Postal Service for communication (WebTable 1). These distance-learning exchanges can be augmented by more personalized interactions delivered through partnerships with museums, science centers, and other local organizations. For large-scale projects, learning is probably greatest during data collection, as participants begin to develop questions based on their field observations. Learning may also happen when participants interact with data through dynamic graphing and mapping tools (eg http://watch.birds.cornell.edu/PFW/ExploreData?cmd=mapRoom). Although the educational value of contributory citizen-science projects continues to be assessed, studies have shown that the experience of collecting data for use by professional scientists is highly motivating, fosters scientific knowledge, and provides opportunities for interacting with members of like-minded communities within local environments; this deeper involvement results in increasingly robust learning outcomes (Bonney *et al.* 2009a; Ballard *et al.* 2012).

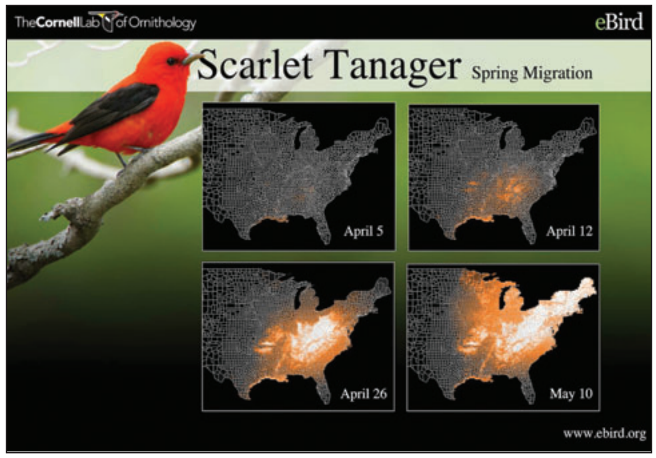

Figure 3. *Scarlet tanager (*Piranga olivacea*) "heat map" showing spatial variation in the probability of occurrence for this migratory species during spring. Hot white areas represent highest probability of occurrence. This and similar heat maps are generated through data-mining approaches with eBird data and made available to participants in the form of downloadable videos on the eBird website.*

In contrast, projects like those organized by Earthwatch, whose volunteers sign on as field assistants for short, educational travel experiences, present opportunities for interaction that are very similar to those experienced by undergraduates working in a university lab. Assessment of citizen-science outcomes for adults suggests that learning is more robust among volunteers who explore their own questions (Bonney *et al.* 2009a). When participant communities devise their own study questions and create projects to address conservation or human-health problems related to ecology and the environment, they often develop stable, personal, ongoing, and collegial ties with professionals and with their fellow participants (Becker *et al.* 2005). As such, community-based projects strengthen scientific capacity, social capital, and inclusiveness of local decision making (Whitelaw *et al.* 2003); they are also an effective means of forming peer-to-peer networks, with potential for augmenting impacts through social learning (Fernandez-Gimenez *et al.* 2008). Based on educational research, substantial inquiry is unlikely to develop in large-scale, contributory ecological monitoring projects unless it is encouraged and intentionally designed for; to this end, some large-scale projects offer inquiry-based curricula intended especially for schools (Trautmann *et al.* 2012).

General approaches to program development

Ecologists seeking to develop a citizen-science component to their research programs currently have many tools and resources at their disposal to initiate the process (Table 1). The first integrative model for citizen-science project development was published in 2009, after receiving input from participants in a 2007 workshop (www.citizenscience.org/conference/toolkitconference; Bonney *et*

Figure 4. *Citizen-science project developers have begun to use various strategies – including contests, incentives, and badging systems – to motivate volunteers, to create a sense of community for participants, and to recognize their efforts.*

al. 2009b). This model – applicable to both participant-driven (collaborative or co-created) and scientist- or institution-led (contributory) projects – often begins with a well-defined team of participant stakeholders, ecologists, education specialists, computer scientists, communications/marketing specialists, and evaluators, who work together to determine clear, project-specific education and research goals. The team then identifies explicit measurable outcomes and the necessary tools and features required to achieve those outcomes through a process of intentional design. Iterative periods of design, evaluation, and revision ensure successful protocols, training materials, recruitment, data entry, and data-sharing infrastructures, while continuing to align scientific and educational objectives with project activities and the abilities/expectations of participants. Gradually, this process adapts the project to its audience, thereby improving learning and research outcomes.

New technologies support integration of internet-based contests and games that provide entertaining ways for citizen scientists to combine learning with data collection. Recently developed platforms like iNaturalist.org (www.iNaturalist.org) exploit the social dimensions of citizen science, in this case by combining all-taxon monitoring with Facebook and other photo-upload tools, social data validation (corroboration), mapping tools, and a smartphone application that is easy to use for novices of all ages (appears in WebTable 1 as a project. Program developers have begun to realize how new technologies can be used to increase participant interest, data quality (using quiz scores as measures of observer variation or observer bias), participant interest, and learning impacts.

■ Participant recruitment and retention

Getting people to contribute to citizen-science projects requires major effort. The mantra "easy, fun, and social" provides a good synopsis of what it takes to recruit a large number of volunteers, but for projects that require moderate numbers and substantial, ongoing commitment, the best approach may be to work closely with specific target audiences and to match the project activities to what the target audience finds rewarding. By focusing on the interests of the target audience at the start, projects can be fashioned to create shared value. An example of this is eBird (http://ebird.org), which iteratively created tools for the large number of existing bird hobbyists based on extensive feedback from the birding community. Partnerships with a diversity of community organizations, even those not explicitly engaged with science, have proven a successful means of growing a participant base (Purcell *et al.* 2012). In the absence of a ready-made target audience, the literature on volunteerism indicates that opportunities for social interaction, enjoyment of the outdoors, and altruistic motivations are important in sustaining volunteer effort (Snyder and Omoto 2001; Van den Berg *et al.* 2009).

Effective communications strategies take into account both participant recruitment and retention, especially for long-term projects. Well-timed press releases that are picked up by national and local media are vital in getting the word out, but continuous forms of communication – such as newsletters, blogs, and social-networking groups – are also important outlets that help to create a sense of community. Also successful are more active forms of communication, such as incentives, certificates of recognition (Figure 4), and quarterly challenges, such as the photography contest, "Funky Nests in Funky Places", which displayed numerous images and participant commentaries on the Celebrate Urban Birds website (WebTable 1). Recently, content-rich, web-based clearinghouses for citizen science have begun to reach out to a large swath of the public, providing valuable information and serving as volunteer recruitment sites for all types of projects (Table 1).

■ Sustainability of citizen-science projects

Strategic collaborations and partnerships may be necessary to garner the resources and participant base required to sustain projects over the long term. The primary challenges for most projects include maintaining funding for cyberinfrastructure, databases, and project leadership. Given the importance of citizen science to ecological monitoring and public engagement with science, support for and recognition of citizen science as an important form of volunteer service – for example, through the America's Great Outdoors Program – can have a worthwhile impact in helping to build a large, dedicated participant base and to sustain valuable citizen-science efforts.

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