Citizen Science: A Tool for Integrating Studies of Human and Natural Systems

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public engagement in science, coupled systems, interdisciplinary research, socioecological systems, coupled human and natural systems, big data

Abstract

Citizen science has proliferated in the last decade, becoming a critical form of public engagement in science and an increasingly important research tool for the study of large-scale patterns in nature. Although citizen science is already interdisciplinary, it has untapped potential to build capacity for transformative research on coupled human and natural systems. New tools have begun to collect paired ecological and social data from the same individual; this allows for detailed examination of feedbacks at the level of individuals and potentially provides much-needed data for agent-based modeling. With the ongoing professionalization of citizen science, the field can benefit from integrating a coupled systems perspective, including a broadening of the social science perspectives considered. This can lead to new schema and platforms to increase support for large-scale research on coupled natural and human systems.

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1. INTRODUCTION

Citizen science is an increasingly ubiquitous term used to refer to a time-honored, evolving practice that engages nonprofessional scientists in the practice of research. Although not a new phenomenon (1–4), citizen-science projects have proliferated in the last decade, becoming a critical form of public engagement in science and an increasingly important research tool, especially for the study of large-scale patterns in nature. In particular, long-running projects and longitudinal data sets, like those gathered by ornithologists [bird monitoring in Europe can be traced back to the eighteenth century (5)], have become critical resources for understanding the impact of a changing climate (6). Recent reviews of citizen science examine the contributions of these long-running projects in detail [see especially (1, 7, 8)]. Citizen science encompasses a wide variety of projects engaging the public in the practice of science, ranging from participatory action research to large Web-enabled efforts that span a wide array of scientific disciplines around the world (see **http://scistarter.com** for comprehensive, up-to-date lists of projects). Criticisms of citizen science do exist and range from questions about data validity (9, 10) to critiques of the use of volunteer labor for the advancement of individual scientific gain (11) and to overreliance on observational and monitoring data in ecological settings (12). These criticisms are outlined extensively by Catlin-Groves (13), Dickinson et al. (6), and Shirk et al. (14). This review illustrates the effectiveness of citizen science for combining ecological research with social science research and raises the possibility that citizen science has the capacity to investigate and provide a framework for complex and dynamic interactions in natural and human systems.

Coupled natural and human systems are highly complex, often self-organizing, and challenging to study (15). The knowledge gains needed to address this challenge require an interdisciplinary approach that draws on the "observations, skills, and creativity of a wide range of natural and social scientists, practitioners, and civil society" (16, p. 1). To date, there are few infrastructures for supporting interdisciplinary studies of coupled systems across a range of geographic scales (17–19). We argue that citizen science can provide a much-needed infrastructure for sustained, in-depth investigations of coupled systems and for the overarching scientific discovery needed to sustain and manage the human-Earth ecosystem.

Coupled natural and human systems: integrated systems in which humans interact with nature

Given its long history of organizing disparate groups of people to perform small tasks focused on a large common goal, citizen science can be leveraged to link social and ecological data in a single research effort. Citizen-science projects that gather only ecological data represent a missed opportunity to gather social data from participants. Likewise, when social scientists study citizen scientists using surveys, ignoring the ecological data that participants are contributing, they miss interesting opportunities to explore the feedbacks between the two. Integrating these two research endeavors with citizen-science methodologies can open up new areas of inquiry and reveal the complex interrelationships among specific aspects of human and natural systems, allowing them to be studied within one integrated data collection system. A natural extension of such a perspective is the potential to extend citizen science to purposefully manage socioecological systems, while simultaneously monitoring the outcomes of such efforts (20, 21).

Leveraging citizen science for interdisciplinary research goals takes some finessing by funders, practitioners, researchers, and information scientists. It is likely that the Web may play a large role in facilitating these efforts, as it already does in many modern citizen-science projects (22–24). Information, communication, and social technologies, including social networking and gamification, can create collaborative (and competitive) environments on the Web to elicit the kinds of public engagement needed to manage collective use of resources (21). Building projects that are able to move between ecological and social data collection requires not only additional, more robust integration of theory from the behavioral and learning sciences, but also an increased investment in the complex cyberinfrastructures needed to collect and manage diverse data sets. Front-end user-interface designs and back-end data infrastructure issues are increasingly addressed by a growing number of research disciplines relevant to citizen science [see, for instance, human-computer interaction (25–28)] but remain undertheorized. More investment in these aspects of citizen science could drive the creation of tools that are increasingly responsive to changing research findings and management strategies for natural and human systems, making it possible for citizen science to realize its potential as a multidisciplinary research tool with the ability to address new scientific agendas that are important for long-term human welfare.

Front end: aspects of a web- or app-based project that participants directly interact with (e.g., user work flows, sets of instructions, or graphic design)

Back end: aspects of a project not directly accessed by participants, but responsible for managing the software functions of the site (e.g., data handling and storage)

2. THE INTERDISCIPLINARY NATURE OF CITIZEN SCIENCE

Citizen science is inherently interdisciplinary, built using both social and ecological principles. Researchers have explored the social and ecological aspects of citizen science to varying degrees in the past five years, but these aspects have largely been treated as independent, rather than as intertwined, entities without consideration of the potential feedbacks among place, ecological, and social data. We review these contributions briefly with a small number of examples before exploring the historical and disciplinary contexts for use of citizen science in coupled systems research.

2.1. Ecological Research Outcomes of Note from 2009 Through 2013

Citizen science provides information on ecological systems that cannot be gleaned without public participation—collecting data over long timescales and across broad geographic areas (29–33). It also provides a scientific window into peoples' private spaces, fostering ecological studies at the personal scale in backyards or even in people's belly buttons (20, 34–36). Rather than providing an exhaustive review, we selected the following examples to illustrate the range of taxa studied and breadth of findings based on citizen-science methods. These examples also cover the different ways citizen science can lead to discovery with observational or experimental tests of hypotheses based on short- or long-term data collection.

Phenology: the study of plant and animal life cycle events and how these are influenced by seasonal and annual climate variations

Checklists: a common data collection structure in monitoring projects, e.g., counts of all bird species observed during a single search event

Existing projects run the gamut from monitoring complex ecological relationships to tracking patterns, such as phenology, geographic distributions, and abundance of organisms. The Monarch Larva Monitoring Project and the Belly Button Biodiversity Project have tested important ideas in the fields of community and microbial ecology (37). The Monarch Larva Monitoring Project and the Monarch Health Project (34) (North America) together contributed data to track the relationship between parasitism and migration in monarch butterflies (*Danaus plexippus*), providing evidence for both migratory escape (the idea that migration allows animals to escape contaminated habitats) and migratory culling (the idea that the rigor of migration weeds out infected individuals) (37). The Belly Button Biodiversity project (North America) used swabs of belly button bacteria to establish that there is unexpected diversity in human belly buttons, but that the diversity found in any given individual tends to be very unique and is very difficult to predict (34).

Other projects have used longitudinal data to examine changing patterns over time and to test hypotheses about environmental versus biological interactions as drivers of change. Plant Watch (Canada) showed that 19 species of plants have advanced the average date of their first blooming flower by nine days in the last decade (39). Voyages Bio Sous-Marine (France/Turkey) used observations by nonscientist divers to establish that the abundance of nonindigenous fish species doubled over a period of six years in the Mediterranean (40). Data-mining checklists from the international eBird Project (29) yielded novel, dynamic bird occurrence maps that revealed changes in movement and probability of occurrence at continental scales, leading to progress in two fields, macroecology and human computation (29). Evolution MegaLab, a European study, successfully gathered a modern sample of an indicator species with a genetically based trait (color) that could be evolutionarily responsive to external pressures (climate, changing predation) and showed that variations in color in the target snail species were likely not the result of changing climate but were caused by changing predation pressures (41). Long-term monitoring projects like these also facilitate rare detections in which many eyes are needed, but only a few will actually find something [see, for example, publications from the Lost Ladybug Project indicating the detection of new ladybug species (42), from NestWatch on a first official record of twinning in bluebirds (43), and from routine cetacean surveys in Israel documenting the first ever recorded instance of a gray whale there (44)]. Together, these projects cover a spectrum of scientific approaches, ranging from post hoc or real-time pattern detection (Plant Watch, eBird, Voyages Bio Sous-Marine) to experimental or observational hypothesis testing (Monarch Health, Evolution MegaLab, Belly Button Biodiversity), illustrating the scientific, geographic, and temporal potential of citizen science. Most importantly, they illustrate the increasing acceptance of the validity of engaging the public in the data collection process and the potential for publication of citizen-science research in top journals.

2.2. Social Science Research Outcomes of Note from 2009 Through 2013

Participants' engagement in citizen science is studied with increasing frequency, but these studies almost exclusively focus on one type of social data—individual and community outcomes that result from citizen-science participation (**Table 1**). Often this research attempts to answer questions about science learning through participation, including seeking evidence of new scientific knowledge, enhanced understanding of the scientific process, increases in scientific thinking, or new skills in accessing scientific information. Although fulfillment of science, technology, engineering, and math (STEM) education goals is a growing interest of citizen-science program developers, learning itself is not a good predictor of changes in environmental behavior (45), indicating that a broader suite of social science approaches is needed for a more robust match to socioecological

Table 1 Summary of research examining select social outcomes in citizen-science projects since 2008

Study		Citizen-science project		Study outcomes			
Author(s) (reference)	Year published	Focal project	Project type[a]	Community-scale outcomes	Programmatic outcomes	Scientific literacy outcomes	Environmental awareness outcomes
Becker et al. (80)	2013	WideNoise	Contributory	NA[b]	NA	Science skills: participants showed increasing skill at recognizing noises, becoming more aware of their environments and distinguishing between noises with greater detail after collecting data	NA
Bonter & Cooper (96)	2012	FeederWatch	Contributory	NA	Design for project success: participant characteristics and data validity	NA	NA
Cornwell & Campbell (144)	2011	North Carolina Sea Turtle	Collaborative	Creation of new communities: evidence of coordinated volunteer efforts to co-manage turtle reproductive success Adaptive management techniques: volunteers change management practices in response to experiences	NA	NA	Changes in environmental behavior: volunteers adopt new proenvironmental behaviors
Fernandez-Gimenez, et al. (145)	2008	Community-based forestry organizations	Co-created	Creation of new communities: created relationships between local forest stakeholders		Science knowledge: demonstrated more complex understandings of ecological systems Understanding of the scientific method: monitors were effective at planning and making technical decisions about monitoring	Changes in individual norms and values about the environment: shifts by monitors toward more sustainable perspectives on land-use practices Adaptive management practices: monitoring directly influenced local management plans

(*Continued*)

Table 1 ***(Continued)***

Study		Citizen-science project		Study outcomes			
Author(s) (reference)	**Year published**	**Focal project**	**Project type[a]**	**Community-scale outcomes**	**Programmatic outcomes**	**Scientific literacy outcomes**	**Environmental awareness outcomes**
Jordan et al. (59)	2011	New York–New Jersey Trail Conference and the Invasive Plant Atlas of New England	Contributory	NA	NA	Science knowledge: increased understandings of invasive plant ecology	Changes in individual norms and values about the environment: increases in awareness of and intention to work against invasive plants Changes in environmental behaviors: no effects found in practices of participants
Kountoupes & Oberhauser (146)	2012	Monarch Larva Monitoring	Contributory	Connection to nature: connecting to nature was found to be a highly valued outcome by adults and children	Design for project success: adults successfully modified activities for children, while retaining scientific protocol	Understanding of scientific method: adults perceived that child participants gained understanding of scientific work through participation	NA
Matteson et al. (141)	2012	Illinois Butterfly Monitoring Network, New York City Butterfly Club, and the New York Chapter of the North American Butterfly Association	Co-created	NA	Design for project success: monitoring any time, any place led to greater detections of butterflies, and seasonal protocols led to greater overall participant retention	NA	NA
McCormick (36)	2012	Louisiana Bucket Brigade Oil Spill Crisis Map (now the Chemical Accidents Crisis Map)	Co-created	Community empowerment: data collected introduced the exposures felt by those in vulnerable communities into federal policy circles, but did not make a clear impact on policy	NA	Access to science information: specifically access to forums where science information is decided on as legitimate	NA
Nov et al. (134)	2011	Stardust@Home	Contributory	NA	Motivations for participation: found that participation was driven by enjoyment and the belief that knowledge should be freely available	NA	NA

Price & Lee (60)	2013	Citizen Sky	Contributory	NA	NA	Science knowledge: found participants, especially those in communication with other participants, learned that their knowledge base was less than previously thought, and there was an enormous amount of potential for future discovery Understanding of scientific method: showed that participants increased their self-evaluation of their understandings of the nature of science Access to science information: participants (especially those socially involved in the project) reported more interest in and access to science information	NA
Raddick et al. (142)	2010	Galaxy Zoo	Contributory	NA	Motivations for participation: found participants typically have multiple motivations for participation	NA	NA
Tulloch et al. (143)	2013	New Atlas of Australian Birds	Contributory	Connection between people and nature: identified factors that affect where people monitor birds in the out-of-doors	Motivations for participation: developed an understanding of what motivates data collection in particular landscapes to improve sampling bias in data sets	NA	NA

[a]Projects are classified here according to the typology in Bonney et al. (47). These classifications include (*a*) contributory, members of the public primarily contribute data, scientists typically design the project; (*b*) collaborative, members of the public contribute data but may also help analyze the data and/or refine the project design; (*c*) co-created, members of the public may be partially or wholly responsible for project design from establishing the topic of interest to collecting data.
[b]NA indicates the study had no findings in a particular category.

systems research goals. Investigating learning outcomes has "become an important component of many citizen-science programs" (46, p. 307) to the exclusion of other social science interests, in part, because evaluation focused on learning is mandated by education funding agencies, which often fund citizen science when other entities do not. Seeking funding from multidisciplinary academic research agencies could help expand the focus on the social dimensions of citizen science from STEM education to a broader set of relevant social outcomes. For the purpose of efforts to understand and successfully manage coupled human-nature systems, it may be critical to transition away from "how much and what do participants learn" to an emphasis on the sorts of complex social and normative factors known to influence environmental behavior (45).

The studies included in **Table 1** cover a wide variety of social outcomes researched in the last five years in ecological citizen-science projects. Outcomes include documented formation of new communities arising as a result of citizen-science projects, human factors that influence project design, science learning, and evidence of changing environmental attitudes. Although there is a lot of interest in citizen science as a tool for learning about science (6, 14, 35, 47–57), results from this research are mixed, and relatively few studies have been done with true controls or even wait-list controls (where some participants are asked to refrain from participating for a set time period as a form of control) (58). In some studies shown in **Table 1**, scientific knowledge increased but without enhanced understanding of the scientific process or changes in the environmental behaviors of participants (59). In others, participants' experiences improved access to scientific information and led to more positive attitudes toward science (60). The lack of consistent results and the variation in what different researchers consider to be of importance make this body of research difficult to interpret and point to the complex nature of studying participants who are subject to a variety of different, difficult-to-measure mediating influences, including attitudes and beliefs, place-based attachments, motivations, and variations in expertise (14). These issues are not unique to citizen science but are common within the field of informal science learning, where researchers have faced similar challenges measuring learning and behavioral outcomes in various out-of-school settings (50).

Resources that develop robust evaluation tools specifically designed for citizen science are being developed (61). Although these tools and the data they help gather are important to educators and to funders interested in the educational potential of citizen science, they represent a narrow band of the social science research that can be done with citizen science. For researchers interested in the human dimensions of natural resource management, which includes disciplines like sociology and psychology, as well as new research areas, e.g., human-computer interactions, citizen-science methodologies can gather many types of social data of interest. The dominant approach to studies of the social outcomes of citizen science is for professionals to collect data about participants. Aligning citizen-science methodologies with coupled systems research can involve participants in collecting data and can expand the types of social science questions that are asked. Efforts to collect social science research data from citizen-science-type crowd volunteers do exist [see, for example, Mechanical Turk (62) or Volunteer Science (**http://www.volunteerscience.com/**), a platform that facilitates participation of volunteers in social research] but are not coupled with ecological data collection, which would facilitate coupled systems research.

3. COUPLED SYSTEMS AND CITIZEN SCIENCE

Ecology is increasingly recognized as an interdisciplinary field with few reliable, concrete tools capable of supporting research to increase understanding of socioecological systems (17, 18, 63, 64). As environmental scientists adopt theoretical frameworks that call for research to attend not only to the natural systems occurring in an ecological context but also to the sociopolitical-economic systems at play as well, tools that collect many kinds of data from the same individual or location will be of paramount importance. The ability to combine a collection of social and ecological data is particularly important in working, or human-altered, landscapes (65), where social and natural systems are perhaps more tightly intertwined (66). Such landscapes are often ignored by researchers who seek to work in more pristine systems, but they are critical arenas for understanding and even improving the public's impact on environmental quality (67, 68). Spatial research on coupled natural and human systems has relied primarily on a combination of local data gathered by researchers and governments or by an aggregation of disparate data sets (69). Tools designed to simultaneously capture both social and ecological information from the same individual agents or locales are novel, yet they are required for agent-based or point-based modeling as a means of understanding how interactions in space and time influence group behaviors and how these in turn influence such important outcomes as species conservation, water quality, and energy use. Agent-based data allow for robust coupled systems analyses, but they require a capacity building, cross disciplinary design and expertise in information science, ecological monitoring, spatial analysis, and the social sciences. Unfortunately, such cross disciplinarity remains the exception rather than the rule in academia (19), with possible exceptions of efforts to combine adaptive management with structured decision making (70).

The field of citizen science has several preexisting methodological tools or tendencies that map neatly onto the study of complexity in coupled systems. Liu et al. (15) characterized the complexity of coupled systems along five dimensions. These include nonlinearity and thresholds (transition points between alternating states); surprises (uncertainty); legacy effects and time lags; resilience effects (ability to adapt to changing conditions through self-organizing mechanisms); and general heterogeneity across relevant space, time, and organizational units (**Table 2**). These characteristics match the ways in which citizen science is already put to use, such as multiscalar analysis, and point to how we might create new citizen-science platforms to address coupled research goals, allowing analysis of social and ecological data with equal depth across multiple scales. Such platforms would support the collection of a broad range of data and allow for expansion of the types of data collected to account for new results and thinking across these different frameworks.

Table 2 Methodological advantages of citizen science for studying complexity in coupled systems (15)

Coupled system dimensions	Citizen-science potential for investigation of Liu's coupled system dimensions
Nonlinearity and thresholds	The geographic scope of some citizen-science projects allows data to flow between social thresholds (e.g., changing policy from country to country) or between nonlinear ecological relationships that often weave between socioeconomic manipulations of landscapes and ecological impacts in nonobvious ways.
Surprises/uncertainty	Citizen science can provide a kind of constant monitoring that leads to the observation of unexpected or serendipitous findings (38, 127–129).
Legacy effects and time lags	Citizen science is the ideal methodological tool for tracing legacy effects of extinct (or even extant) human-nature couplings by providing access to individuals and communities with historical understandings of particular socioecological contexts (19, 38).
Resilience effects through self-organizing systems	Couplings between on-the-ground communities and natural contexts can be created through citizen science, often leading to pathways to resilience for both social and ecological systems (21, 101, 130–132).
Heterogeneity	Citizen science is an existing tool for collecting data across an extremely heterogeneous set of variables, including social, ecological, behavioral, temporal, and spatial system inputs. Developers of citizen-science projects often possess the skills necessary to generate the partnerships required to work across interdisciplinary boundaries.

3.1. Expanding Social Data Collection with Citizen Science

As mentioned above, evaluation of the impacts of citizen-science participation on the participants or on data quality or quantity comprise only a small sliver of the wealth of social science research that can be conducted within citizen-science projects designed to support coupled natural and human systems research. Geographers have pointed to the benefits of spatially explicit social science for more than a decade (71), although the social data typically used are primarily from large government databases rather than from paired samples that link individual social data to specific ecological data. Nearly all large-scale ecological monitoring projects involving citizen science collect data on the latitude and longitude of each observation. Researchers have certainly had success integrating citizen-science data with external, contextual data, such as weather or land-cover data, to answer questions about geographic or temporal patterns of variation in ecological trends (29, 30, 72, 73). At the same time, researchers have sought to combine large-scale, but differently collected, data on ecological and human landscapes to ask questions about how spatial heterogeneity in human interaction with resources influences the function of urban ecosystems (74). One study utilized the natural urbanization experiment created by the presence and eventual removal of the Berlin wall to show that bird brain size changes in relation to human socioeconomic conditions, growing larger as regions gain wealth (75). Citizen science, however, has only rarely included spatially explicit social science data alongside landscape data.

Collecting coupled data (i.e., data that varies in type, but is specific to one point in time, one location, and one agent or group of agents) is currently very rare despite requiring only a small extension of existing citizen-science projects. More common are projects that use socioecological perspectives to theorize or carry out the work. This usually involves collection of both ecological and human dimensions data within a single community or system and analyzing those data using mixed methods approaches. These quasi-coupled approaches are primarily found in projects that self-identify as public ecology, civic ecology, civic science, and community-based management, but these approaches are good starting points for examining what this kind of work might look like within a citizen-science frame. Projects from this tradition often involve edgework (i.e., work at the edges of fields) and boundary crossings (i.e., where individuals move into each other's domain of expertise) (76). Tidball & Krasny (77) describe how citizen-science methodologies can be used to facilitate both information gathering and resilience in disaster zones. They describe the use of data collection in post-Hussein Iraq to help displaced Marsh Arabs reconstruct their native landscape after devastating government actions destroyed local ecological systems in the Mesopotamia marshes. They suggest that active participation in data collection and analysis helped Marsh Arabs rebuild their lives and landscapes, and they argued that this would not have happened with top-down methods, which are usually less sensitive to the historical economic context of the region and the lived experiences of the locals.

In another example, ongoing efforts to navigate the socioecological complexities of coal mining gave rise to a citizen-science framework designed to parse out the social, environmental, and economic factors influencing the local mining industry (76). In this case, researchers propose engaging in a distributed network of individual participants to collect data not only about the environmental conditions in regions affected by mining, but also about the sociopolitical conditions, such as aesthetics, traditions, economic roles, and personal values that shape local relationships with the mining industry. Collection of these data could enhance the value of the monitoring data by giving a more complete picture of this complex coupled human-nature system. Contextualizing mining not only from an economic or ecological standpoint but also from an informed position that includes the perspectives of residents is likely to uncover points of conflict and flexibility within the system that are vital to community-based management and structured decision-making processes.

3.2. Technology for Collecting Social Data

Although some citizen-science projects do not use the Web, or any digital technology at all, Web applications are already an important part of many projects, especially those attempting to reach a large audience or achieve data collection at broad geographic scales. Understanding of coupled natural and human systems can be greatly enhanced with the coordinated, location-specific and/or longitudinal data collection afforded by Web-based citizen science. The form and flexibility of Web-enabled citizen science is well suited to a broader scale, closer to what has been suggested by scholars envisioning next steps in the development of coupled systems research. The advantages of using technology for coupled research include having the ability to obtain agent-specific data to create powerful, coupled data sets and the creation of social platforms to create communities of practice, whose members can serve as agents of change in management practices.

Coupled data can be gathered in at least three ways:

1. Because participants are the social environment for their own ecological data, expanding the data they provide via questionnaires, tracking their online behaviors, or asking them to provide data on their practices yields point-specific pairing of social and ecological measures, which can then be used in individual-based modeling of socioecological feedbacks and outcomes. These data can be used to characterize attitudes, values, motivations, and behaviors or used to examine how human perceptions vary in time and space. For example, Mappiness, a smartphone application (app), uses mobile devices to randomly request information about people's surroundings (outdoors/indoors, alone/with others, etc.) and their state of happiness. Researchers discovered that people tend to report that they are happier when they are outside (78).
2. Participants can be asked to gather qualitative or quantitative data on other people's behaviors, e.g., foot traffic, smiling frequency of passersby, and density of lights on in buildings within a certain radius, all of which represent participants' assessments of local behaviors. Several European researchers used mobile technology and social networking to monitor a variety of socioecological variables from health variables, such as noise pollution (WideNoise) to the number of beggars seen on the street during daily activities (79). In WideNoise, participants not only recorded noise levels using the built-in functions on their mobile devices, but also identified the source of noise and assigned those noises a set of perceptive scores (love/hate, calm/hectic), recognizing that noise is both a standardized environmental output and the result of human perception. The researchers established that, unless a noise was characterized by participants as natural, the participants' tendencies to characterize the noise as hated and their feelings as hectic increased with volume (80).

   Collecting such data can be especially critical after events like natural disasters where the spatial heterogeneity of human welfare might otherwise be difficult to measure. The efforts undertaken by the Bucket Brigade in Louisiana, following the Deepwater Horizon oil spill, gave affected individuals and communities a chance to layer their personal observations of oil spill impacts (e.g., toxic smells or negative health effects) over officially recognized data, giving more granularity to the sparse monitoring undertaken by the US Environmental Protection Agency and providing a chance for communities to help define and document the impacts beyond those outlined by authorities (36).
3. Handheld sensors hold considerable promise for integrating data that examine human industrial impacts and peoples' responses to them; the smartphone app walkit.com used sensors to measure air pollution on people's walking routes and then created visualizations of the UK city of Cambridge on the basis of the readings. Such data can be combined with public socioeconomic data for spatially explicit modeling, combining individual-based

environmental data with landscape-scale social data to examine relationships and feedbacks among ecological and social factors. Paulos et al. (81) have noted that the growing use of mobile technology in daily life is ushering in an era of nearly ubiquitous data generation. These digital data are generated during mundane daily activities and communications, such as online searching and purchasing records, blogs, Twitter, use of the electrical grid in the home, and increasingly by cars with computers (82).

For citizen-science projects in which participants submit data via smartphone apps, it is possible to receive permission to mine data on the location and movements of participants (83). These data can augment intentionally submitted data to generate insights about how participants' behavioral practices influence data quality and ecological outcomes. For example, cell phone traces can be used to detect the overall level of mobility, including whether people are using cars or other slower forms of transportation, generating behavioral data that can be included in analysis of associations between lifestyles and environmental, ecological, or even happiness variables. Patterns can be gleaned from wireless networks, such as the density of people in the immediate vicinity or even economic status (84), which can be stored alongside participants' observations. Where sensors are used in conjunction with cell phones, air quality can be monitored along with data gathered by participants, as can important predictive ecological variables, such as light pollution, which disrupts the circadian rhythms of all taxa, as well as insect life cycles and bird migration (Globe at Night Project), and noise pollution, which is increasingly recognized as a factor in human and animal habitat quality (80, 85).

Smart grid: a modernized electrical grid that uses communications technology to automatically gather information about the behaviors of suppliers and consumers

Unintentionally produced data can also be gleaned from the growing network of Internet-enabled sensors, such as smart grids. For some types of critical data, such as those about behavioral practices (e.g., irrigation or energy use), use of surveys may be unreliable if behaviors change rapidly or are likely to be systemically over- or underestimated by participants (86). In these cases, the use of incidental data (i.e., data collected via sensors, monitors, or mobile devices) may produce more accurate accountings of participant activities. Use of these data are not without urgent privacy concerns, and the last five years have seen numerous complaints about the controversial use of global positioning systems (GPS) to trace consumer behavior (87). This issue continues to be a concern for the citizen-science community when participants enter location data with their observations and is even more of a concern when children and youth are active participants in projects. Standards for the use of such data, especially with vulnerable populations, are starting to be outlined to unambiguously address concerns and continue the ethical practice of citizen science (88).

4. GROWING CITIZEN-SCIENCE CAPACITY TO SUPPORT COUPLED SYSTEMS RESEARCH

Moving citizen science toward coupled systems research requires continued development in the field to address issues of project sustainability; standardization of a knowledge base; increased infrastructure support; and greater attention to project design to promote the collection of quality data, the recruitment of participants, and new tools to support analysis of feedback loops between participants and natural systems. In this section, we propose that the substantial efforts undertaken in the past six years to move the field forward mean that citizen science is poised to accomplish these goals. These efforts, along with some recommended principles for the design of effective citizen-science projects, are outlined in this section.

4.1. Challenges in Funding Interdisciplinary Citizen Science

Sustaining citizen-science projects is a major challenge, yet coupled systems research requires long-term projects that can serve as platforms for socioecological research. The handful of long-running citizen-science projects (for example, the Christmas Bird Count or the National Weather Service Cooperative Observer Program) have contributed invaluable data sets to researchers interested in questions that were not on the table when the projects started. Most long-term citizen-science projects have been able to tap into private and public funding through a diversity of disciplines ranging from education to computer science. One impact of relying on diverse, cross disciplinary funding initiatives, or trying to fit the goals of foundations, is that doing so can influence the core goals of the project. Given existing funding opportunities, program developers sometimes choose to redefine the mission of their project to align project goals with what they perceive of as achievable, fundable education-based outcomes (57). In these instances, measuring learning impacts takes on increased significance, even in the absence of a new theory or well-established methodological tools for measuring learning impacts in complex natural settings (46). In this regard, being able to obtain large cross disciplinary grants for coupled systems research using citizen science as the basic platform would both provide superior opportunities for longitudinal research and help to sustain projects.

Leveraging funding for citizen science for coupled systems research is partially dependent on fostering more interest in interdisciplinary research by a diversity of academics and funders. Cross disciplinary work can be incentivized with funding and training at the edges of fields, but these kinds of opportunities are often dependent on professionals themselves deciding interdisciplinary work is worth the investment of their time. Although the citizen-science community has had to be inherently cross disciplinary, it has not yet benefited fully from what might be a broader shift within academia toward an acceptance of the value of interdisciplinary work.

4.2. The Professionalization of Citizen Science

Advancing this new field requires new training opportunities, professional experiences, shifts in professional norms, and clear pathways to funding in support of interdisciplinary work (19). The field of citizen science is moving this along, in part, by demonstrating innovation through interdisciplinary work. Citizen science has already begun to elicit interest from researchers in a wide spectrum of fields, including human geography (35, 51, 89), communications, science and technology studies, and information science (e.g., data mining) (30, 72, 90). Today, we have seen some bridges form across disciplines, such as studies of human computation in crowdsourcing citizen-science environments (83) [evidence that crowd or collective intelligence arises from getting a diverse group of individuals engaged in tackling scientific problems (91)] and advances in machine learning [a branch of artificial intelligence research that is also advanced by crowdsourcing (8, 92)]. Broadening the scope of interest in citizen science speaks directly to growing recognition of its capacity to do more than just engage volunteers in dispersed data collection.

Some have noted that citizen science is coming-of-age (93, 94), but the term professionalization, which refers to the process of constructing a centralized knowledge basis for a field, is a more accurate description (95). The past six years have seen a growing movement toward production of this knowledge base. There has been an explosion of informational resources for citizen science and a growing interest in establishing citizen science as a field of inquiry in and of itself. Scholarly works document this rise, notable among them a special issue on citizen science in *Frontiers in Ecology and Environment* (1, 23, 32, 46, 94, 96–99); a book, *Citizen Science: Public Participation*

Professionalization: the process of constructing a formal knowledge basis for a newly emerging field *in Environmental Research* (100); and several professional reports including *Public Participation in Scientific Research: Defining the Field and Assessing Its Potential for Informal Science Education* (101), *Understanding Citizen Science and Environmental Monitoring* (53), and the *Guide to Citizen Science: Developing, Implementing and Evaluating Citizen Science to Study Biodiversity and the Environment in the UK* (52).

There have also been several meetings focused on this same kind of knowledge production work. In 2007, a group of researchers met to discuss creating a tool kit for citizen science; the meeting resulted in the creation of the CitizenScience.org, an organization with a website created to guide and provide resources to those wishing to start new citizen-science projects (102). In Europe, the biennial *Citizen Cyberscience Summits* started in 2010 (**http://cybersciencesummit.org/2010-summit/**) to gather scholars from a number of fields, including human-computer interaction, spatial analysis, and human computation, to discuss all cyber-enabled science, including citizen science. In 2011, researchers and practitioners convened the *Enhancing Biodiversity Conservation and Environmental Stewardship through Public Participation in Scientific Research* conference (103) to answer questions about how citizen-science practice can help bridge the divide between scientific research and conservation practice. In the same year, the Lay, Local, Traditional Knowledge and Citizen Science workshop was hosted by the European Environment Agency to integrate citizen science with funds of knowledge approaches (104). A little over a year later, the community (several hundred strong) came together at the Public Participation in Scientific Research conference (105), a special workshop preceding the 2012 meeting of the Ecological Society of America. Additionally, workshops, panels, and sessions on citizen science are increasingly common at disciplinary conferences, such as the 2013 citizen-science panel at the American Geophysical Union, the workshops on citizen science and forming scientific communities online at the 2014 Pacific Division Meeting of the American Association for the Advancement of Science, and the session on citizen science at the National American Association for the Advancement of Science general meeting.

These events have worked to build a community of practitioners and researchers now forming new professional organizations. In Europe, the European Citizen Science Association (**http://ecsa.biodiv.naturkundemuseum-berlin.de**) launched in June 2013, and an international Citizen Science Association is also taking shape (**http://citizenscienceassociation.org**). Professional organizations like these not only aim to provide a formal place for the exchange of ideas about citizen science, including best practices, technology sharing, training, and publication opportunities, but also provide opportunities for university training, access to funding, and the increased ability to shape policy and to influence wider professional opinion. Such steps are an important part of legitimizing a field and aiding in the acceptance of interdisciplinary work.

4.3. Infrastructure Support

Part of the knowledge-construction process for citizen science has also included the development of specialized technological tools. One of the challenges facing any new citizen-science project is the development and maintenance of the technology necessary to support the participant community and the data submission process. Such tools facilitate data collection, proper management and archiving of data, and the visualizations and dissemination of data. These tools can be lumped into two categories describing their primary role in a citizen-science project: front- and back-end tools.

Front-end tools include technological interfaces, protocols, and apps that participants interact with directly and that are often informed by scholarship from psychology, behavioral economics, human-computer interaction, and education. Back-end tools include behind-the-scenes technology that involves proper handling and storage of data, which rarely involves interaction with the participants. There are a growing number of efforts, including CitSci.org, FieldScope, Eye on Earth, Socientize, and Citizen Science Alliance, that are attempting to provide generic front- and back-end tools to be used by any community, scientist, or individual to build, organize, and manage their own citizen-science projects (23, 106, 107). At least one group is focused on the development of back-end, open-source, data-analysis tools for citizen science, addressing concerns about the technical expertise needed to analyze much of the big data generated through citizen science (108, 109). Efforts like these are responding to an increasingly urgent recognition that new citizen-science projects struggle to collect, handle, and store data in ways that make that data useful to researchers and the public. Challenges include addressing issues such as interoperability with other citizen-science data and data from other sources to maximize their potential benefits (29, 30, 49, 96, 108–113).

Interoperability: the ability of different information technology systems to work together to allow for information exchange

4.4. Designing Citizen Science for Coupled Systems Research

The creation of citizen-science projects includes a myriad of important steps from development of a research question to technology design (47). Here, we focus on the human actors in coupled systems and how to engage and sustain their participation. To realize the goals of studying coupled systems using citizen science, it is important to understand how to grow a sustainable participant base for a project that is likely to provide the kind of data needed to analyze a given system. Attracting and retaining participants is a complex process that depends on several behavioral, cognitive, and social characteristics, as described below. Likewise, coupled systems have characteristics of their own that can also depend on some of the same behavioral, cognitive, and social characteristics that influence citizen-science participation. These are broadly lumped into place-based and interest-based categories.

4.4.1. Place-based communities. Effective citizen-science projects commonly build on the existing relationships people have with their environment (35). These are often highly developed, historically established relationships that bring with them a wealth of information. Citizen-science activity is typically localized, both in the case of small, community-driven projects, such as those focused on monitoring the health of a single lake or stream, and in large national and international projects where data collected at a large scale are aggregated within a generalized schema [see, for example, the National Phenology Network (35) or BirdLife International].

The place-based nature (for participants) of much environmentally focused citizen science is likely one of the reasons for its shared personal and scientific value. This is particularly true for ecological research, which benefits from close observations by experts (114). Likewise, many socio-ecological entanglements are, at least partially, highly dependent on local interactions between people and places, making existing citizen-science projects potentially valuable for supporting the management of intertwined social and ecological problems. Expertise, in this case, may be better determined by proximity and familiarity with a particular ecological context than by formal scientific training (97, 115). Thus, people who live in, or frequent, a particular place may have an intuitive and scientifically valuable understanding of that area, which would be extremely difficult to acquire without time and similar experiences in that place. This could bias them or it could allow them to notice exceptional cases and to gain access to important data resources that are not widely known.

For example, the English Channel fishing community, composed of fishermen from all of the countries surrounding the English Channel in northern Europe, was found to be a highly accurate source of information about the Channel ecosystem (116). Their reports had greater power to detect change than surveys carried out by teams of scientists. This type of knowledge is referred to as traditional ecological knowledge (117, 118) and is described as "a cumulative body of knowledge, practices and representations that describes the relationships of living beings with one another and with their physical environment. Such knowledge is considered to have evolved by adaptive processes and has been handed down through generations by cultural transmission" (119, p. 463). Traditional ecological knowledge is widely acknowledged to complement scientific understandings of phenomena, but in more dire circumstances, it also serves to bring to the table the primary stakeholders, people who are most affected by the findings and who must be part of the solution (120).

Researchers have analyzed changing Arctic conditions by combining local hunters' observations with field data documenting current uses of sea ice by local indigenous populations (121). They also tracked the effects of climate change risk in Alaskan native communities and demonstrated that local knowledge corroborated the information garnered by professionals in assessment reports and also included an additional layer of integrated sociopolitical information about changing whale and fish migration routes, changes in the shapes and sizes of local beaches, and less predictable predominant wind patterns. This information would be important in any productive attempt to move from assessment to adaptive planning (117, 122). In the Soliga community of southern India, invasive plant ecology has benefited from local insights revealing radically different ecological mechanisms at play than those conceived by professionals alone (123). Scientists believed fire promoted the spread of invasive *Lantana* species, but the more nuanced perspective of locals revealed that, in some cases, fire actually suppressed *Lantana* invasion.

In these cases, rather than marginalizing the affected communities, researchers engaged them in a collaborative process. The results were a strengthening of the research through participation of local communities and a sharing of resources, including methodologies, generalized knowledge, institutionalized expertise, and even a place at the political table where decisions were made (98, 124). These benefits likely arise for any local community participating in a research effort, not just those marginalized by existing social and institutional power structures, and they allow for closing the loop between knowledge building and decision making because stakeholders are already engaged.

These insights are not restricted to local projects involving indigenous knowledge because even national- and international-scale citizen-science projects, like the National Phenology Network and eBird, build off of participants' intimate knowledge of place. In both of these cases, participants report information at a local scale, often highly dependent on knowledge of local plant species, local birding hotspots, and phenological timing that applies to specific geographic locations and conditions.

Although citizen scientists have been described as a network of human sensors (89), this presents a limited and perhaps constraining view of the potential for more robust two-way socioecological interactions that are of interest to researchers studying coupled natural and human systems (21, 85, 125). Citizen-science participants, like learners more generally (126), are both producers and consumers of information. In coupled systems, information flows through education, social networks, and media outlets, playing a critical role in the types of feedback loops that characterize the relationships between human and natural systems, potentially creating place-based communities that serve as a nexus for both learning about coupled systems and introducing new information (data) that feeds back on management.

4.4.2. Interest-based communities. Citizen science rooted in the experiences of participants is thought to strengthen both scientific and educational goals (99). Basing citizen-science project design on existing hobbies and amateur expertise (127) not only takes advantage of a preexisting participant base (128) but also removes some of the up-front need for intensive education, leading to easier, often more successful, participation (129), and gives "purpose to an activity already being conducted" (130, p. 372). Bonney et al. (47) note that one way to generate successful projects is to engage citizens and scientists in ways that take advantage of existing shared goals or that build upon a shared interest, rather than convincing one or the other party to take on the goals of the other. For example, the Old Weather project builds on participants' preexisting interest in tracing family ancestry and understanding more about the lives of their ancient relatives. Old Weather invites people to read and transpose the daily written records from ships logs written between the 1780s and 1950s. These records mention ships' passengers, which participants eagerly comb over, looking for mention of their families, but in service of the project, they also record detailed records of weather connected to geographic points and dates. The researchers see the weather information as a valuable source of historical climate data, while the participants have access to a valuable source of ancestral information provided by the project organizers. Studies of this project show that even the use of external motivation tools, like gamification elements in the online tool, depend on a preexisting interest to motivate intense participation (28).

The French Garden Butterflies Watch also takes advantage of people's preexisting interest in the butterflies they see in their gardens. The citizen-science project is additive, building on this existing interest, while layering in observation protocols that help turn participants from making casual observations to collecting systematic data that is more scientifically useful. Participants openly admitted little experience in identifying butterflies at the morphospecies level, but many already had an interest in nature and liked that the program specifically targeted their backyard and valued their observations (131). The difficulty of identifying insects in citizen-science projects is well documented (132, 133), and at least one project focused on bees has adapted its goals, changing its protocols to reflect participant expertise at identifying bees at the level of family rather than genus or species, rather than invest in extensive curricular interventions to help participants learn to identify insects well enough to report the species (132).

Designing projects using place- and interest-based communities provides a natural window into the existing connections people share with the natural world. Well-designed citizen science, however, can also grow relationships between humans and nature by mediating interactions and even producing feedback loops that allow for adaptive management. For instance, the YardMap project asks people to create maps of their yards, highlighting the kinds of gardening they do, the sorts of sustainable actions they take, and the birds and plants they see. Many people are already interested in gardening and attracting birds, so they are especially invested in their yards as personal spaces, making it easy to attract participants to the project. Even though self-selected participants were already invested in these topics, participating in the project creates new socioecological interactions, including opportunities for reflection on changes they see in their plant and bird communities and exposure to different social norms; this exposure can alter dynamic interactions within an existing coupled system.

4.4.3. Social interaction in citizen science. Some have suggested that citizen-science participation is partially dependent on participants developing a sense of belonging, indicating positive feedbacks between socializing the practice of citizen science and levels of participation, effort, and outcomes (134) and emphasizing that citizen science, like most endeavors, is a social process (33, 135). Project developers of recently created citizen-science platforms, e.g., FieldScope (136), have begun to express ambitious goals, for example, to create communities of participants who will engage in the design of online data-collection technology. At least two studies have found a positive relationship between social involvement and science literacy outcomes (60, 135). This is not surprising given the ample evidence that learning is a highly social activity (137) that often depends on the formation of communities of practice (138).

The development of communities of practice around citizen science raises questions about whether these communities bring together diverse stakeholders or are instead fairly homogenous.

This leads to wondering whether they can be leveraged to negotiate new stewardship behaviors among participants or instead create a new culture with its own norms of behavior. When projects move away from the soft governance model (8) and provide opportunities for interactions among individuals, this creates a network of interactions and co-produced meaning, leading to opportunities for new ways of thinking about existing socioeconomic-environmental conditions (139). These emergent ways of thinking may be very different from what happens with orchestrated and seemingly top-down stakeholder engagement processes. Social relationships are known to lay the groundwork for the adoption of new proenvironmental behaviors, which often depend to a great degree on normative rather than regulative or rational forces (45).

5. CONCLUSIONS

Citizen science has the potential to advance the coupling of ecological research with social science research, especially because it holds promise for collecting multiple types of information on individual actors. Already an interdisciplinary field, citizen science generates important ecological results as well as results from studies seeking to understand the impacts of participation on individuals and communities (e.g., whether an individual gains any scientific knowledge). Although these kinds of research are important, it is only rarely that citizen-science methodologies have been used to couple both social and ecological data arising from a single actor or location.

Coupled systems research is a challenging field of inquiry that is fundamental to understanding how critical interactions between humans and nature influence ecosystem changes. Its progress has been hampered by a lack of infrastructure to support sustained, longitudinal, and spatially diverse studies needed to build coupled databases. Citizen-science methodologies take advantage of distributed networks of people, enabling researchers to gain access to ecological information as well as social data originating at the same points over long timescales, across broad geographic regions, and in different socioeconomic systems. They also hold the potential to create new self-organizing, coupled systems that can be studied and leveraged to increase understanding of interactions and feedback loops influencing adaptive management outcomes.

Much of the potential for success of coupled systems research using citizen science relies on use of smart digital technology, providing easy, adaptable access to large audiences on the Web. This will inevitably include the use of mobile technology to enable dispersed, accurate data collection and use of always-on monitoring technologies to combine intentionally reported data with data collected passively, for example, using cell phone traces. Overtime, the field of citizen science could contribute substantially to the creation of powerful coupled systems tools, realizing its potential to address new scientific agendas framed by increasing concern for the Earth system. Its role is likely to become ever more important with recognition that direct human effects on ecosystems are so great that we have effectively entered a new geological epoch in which understanding and managing change is of paramount importance (140).

SUMMARY POINTS

1. Citizen-science projects are gaining momentum as tools for ecological research and as a means for public engagement with and learning about science.
2. As the field has matured, it has grown from tracking not only ecological data submitted by participants but also social outcomes demonstrating changes in individuals as a result of participation. These data, however, are limited in that they are not often paired with ecological data.

3. The broader environmental sciences research landscape has recognized the importance of pairing ecological data with social data to study coupled human and natural systems, but it is generally recognized that there is a lack of concrete tools for investigating these complex systems.
4. Citizen science, already engaged with social systems and ecological systems, is poised to become a tool for the study of coupled systems.
5. New technologies make pairing ecological data with social data using citizen science even more accessible.
6. As the field of citizen science undergoes a process of professionalization, it has the opportunity to grow in directions that can further support the infrastructures, knowledge base, and innovation necessary to overcome some of the limitations inherent to citizen-science data and to realize its potential as a coupled systems research tool.

FUTURE ISSUES

1. Citizen science, although inherently interdisciplinary, faces some challenges in integrating more robust knowledge from social fields, such as behavioral psychology, economics, human-computer interactions, and sociology. Researchers in these fields need to see value in partnering with citizen-science providers.
2. Citizen science, like all interdisciplinary research, can have trouble finding sustained funding sources. Becoming overly reliant on educational funding may continue to drive social research in citizen science toward the investigation of STEM outcomes, rather than helping it focus on coupled systems research goals.
3. Working with coupled systems research will make citizen-science data sets even more complex than they already are. Investing in infrastructure and training to support the storage, handling, and analysis of these complex data will be critical to realizing this goal of handling the increasingly complex data sets that will result from coupled systems research.

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