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Power of the People: A Review of Citizen Science Programs for Conservation

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Highlights

- Consistent definitions, protocols are needed to improve the citizen science field
- Citizen science provides benefits to participants, scientists, society, environment
- Challenges relate to economics, volunteer management, data analysis
- Experimental design, data management, data sharing are key areas to plan carefully
- Best practices for developing and running projects are discussed

Abstract

Citizen science is a rapidly growing field whereby volunteers can collect and/or analyze data to contribute to research and gain an appreciation for the environment. There are countless programs currently underway around the world: some have clear scientific hypotheses being tested and others are simple data gathering; some are designed and led at the grass-roots level while others are done by academics. This review focusses on best practices for the development and running of citizen science projects to make them successful. It includes discussion around different methods of experimental design, data collection, and analyses; how participants are recruited, engaged, and rewarded (including who participates and why); the effect of participation on the volunteer's knowledge and actions; and the impact programs have on policy and other conservation actions. While there are several challenges that projects face, and more research is needed in various areas, the many benefits support the continued expansion of citizen science projects.

Keywords

Citizen science; community science; volunteer management; experimental design; naturalist; citizen scientist

1. Introduction

While humans have been sharing observations of the world around them for millennia (Miller-Rushing et al., 2012; Pastor, 2018; Silvertown, 2009), the domain of citizen science is a relatively new area of research and discovery. Dating to the early 1990s (Follett and Strezov, 2015; Hannibal, 2016; Irwin, 1995), citizen science is a fast-growing field covering a wide range of topics and taxa, from human microbiota (del Savio et al., 2016) to distant galaxies (Edwards and Gaber, 2014). As a newer science that is being practiced globally in different forms, with different definitions, frameworks, and protocols, it has not yet settled into a cohesive whole. Yet to fully realize the potential of citizen science, it is necessary to identify what works well and what does not, and where more research is needed to develop new techniques.

Although still young, the field of citizen science has received review articles on a wide variety of subjects. For example, new technologies (Ceccaroni et al., 2019; Newman et al., 2012), methods of data analysis (Cooper et al., 2012; Steve Kelling et al., 2015; Zipkin and Saunders, 2018), assessments of data credibility and quality (Aceves-Bueno et al., 2017; Freitag et al., 2016; Kosmala et al., 2016), impacts on policy (Greenwood, 2012; Hecker et al., 2019, 2018), economic implications (Sauermann and Franzoni, 2015; Theobald et al., 2015) and impacts on and by volunteers (Bell et al., 2008; Firehock and West, 1995; Lewandowski and Specht, 2015; NAESM, 2018; Schuttler et al., 2018; Shirk et al., 2012) and on and by stakeholders (Sterling et al., 2017). Additionally, there have been several reviews on the impacts of citizen science on conservation efforts (Ballard et al., 2017; Chandler et al., 2016; McKinley et al., 2017; Newman et al., 2017; Poisson et al., 2020; Silvertown et al., 2013). Other reviews have been conducted on additional aspects of citizen science programs (Aceves-Bueno et al., 2017; Conrad and Hilchey, 2011; Danielson et al., 2014; Pocock et al., 2015; Sullivan et al., 2017, 2009; Wiggins and Crowston, 2011).

Governments, universities, and non-profit organizations are now coming together to support the development of common frameworks and guides (Blaney et al., 2016; Bonney et al., 2009a; Citizen Science Association, 2020; CitizenScience.gov, 2020; NEIWPCC, 2016; Socientize Consortium, 2013; Strasser et al., 2012; Tweddle et al., 2012; Wiggins et al., 2013). To maximize project resources, common challenges should be noted and avoided or addressed.

This paper provides an expanded, cohesive overview of what citizen science is, who it involves, and the reasons to use it. It covers small, in-person projects to large, online ones. It focusses on best practices for developing and running citizen science projects through the identification of common challenges faced and solutions to them, and includes suggestions on how to make projects more successful. These include areas such as experimental design, data analysis and quality control; volunteer recruitment, training, and retention; motivations for and effects of participation; data management and security; data sharing and project overlap; obtaining funding and other resources; economic, social and political controversies; project assessment and evaluation; and new technologies.

2. Methods

To locate relevant sources, searches were conducted through Google Scholar using key words such as “citizen science” and “community science” with additional qualifiers including “challenges”, “techniques”, “review” and “research”. The titles and abstracts of the resultant papers were read and evaluated and if they appeared relevant, the paper was given a deeper review. Relevant references cited within this first group of papers were then obtained, and their content and references evaluated, with more papers being targeted for review. This process was ongoing, with the main searches occurring from January to June 2018. Additional searches were also conducted via Google Scholar and institutional libraries during the writing of this article to locate information on specific topics not adequately captured using those original search terms.

3. Results and Discussion

Using the snowball approach described above, over 300 papers were selected for a deeper review. These included original research through review articles, on scales from local city or regional based studies through national and international ones. While most of the research was based in North America and Western Europe, others were from Africa, Asia, South America, and other parts of Europe. Many were focused on ecological topics, from systems to species, and covered a range of taxonomic groups, from insects to mammals and plants. Projects were generally led by professional scientists, but citizen scientists also contributed to project design in some cases.

3.1 What is citizen science?

3.1.1 Definition

There is no consistent definition for citizen science (Auerbach et al., 2019; Eitzel et al., 2017; Heigl et al., 2019; McKinley et al., 2017; NASEM, 2018), although a spectrum of concepts and terminologies exists (Table 1). It commonly refers to a scientific program, overseen by professional scientists, where non-professional volunteers collect and/or analyse data that are then used to advance scientific knowledge (Auerbach et al., 2019; Eitzel et al., 2017; Heigl et al., 2019; McKinley et al., 2017; NASEM, 2018). These projects can provide baseline or monitoring data, answer research questions, increase stewardship and awareness, and influence conservation actions and policies (Acorn, 2017; Bonney et al., 2009b; Conrad and Hilchey, 2011; Follett and Strezov, 2015; Jordan et al., 2016; Le Féon et al., 2016; McKinley et al., 2017; Ryan et al., 2018; Thomas, 2016; Wiggins and Crowston, 2011).

Citizen science may include certain types of games (Kawrykow et al., 2012; Khatib et al., 2011; Ponti et al., 2018) although some authors disagree as the players do not always understand the science behind the game (NASEM, 2018; Ponti et al., 2018). In Europe, the term can also relate to engaging the public in science discussions and policy making (Irwin, 1995). Projects that are focussed on public relations or science/environmental education (Russell, 2014), or that do not produce or share new knowledge (Acorn, 2017; Ballard et al., 2017; Miller-Rushing et al., 2012; NASEM - National Academies of Sciences Engineering and Medicine, 2018), do not fall into the definition of citizen science that is used here.

Table 1. Other terminologies used for citizen science.

Term	Reference
Community science	Conrad and Hilchey, 2011
Community-based management	Conrad and Hilchey, 2011
Community-based monitoring	Conrad and Hilchey, 2011
Community and citizen science	Ballard et al., 2017
Crowd-sourcing*	Eitzel et al., 2017 (but see e.g. McKinley et al., 2017)
Participatory monitoring networks	Bell et al., 2008

Participatory research	Hannibal, 2016
Public participation in organized research efforts	Dickinson and Bonney, 2012
Public participation in scientific research	Shirk et al., 2012
Voluntary biological monitoring	Conrad and Hilchey, 2011

*Some authors explicitly include crowd sourcing in with citizen science, where the term involves large numbers of volunteers collecting data often with small specific tasks to accomplish. Others do not include crowd sourcing, where participants are only involved in basic data processing and analysis with no connection to the underlying science.

3.1.2 Topics covered by Citizen Science projects

Many projects involve a natural science topic (see broad discussions in e.g. Griffin Burns and Harasimowicz, 2012; Hannibal, 2016; Russell, 2014; Theobald et al. 2015), ranging from aligning DNA sequences (Kawrykow et al., 2012) and folding proteins (Khatib et al., 2011) to capturing information on a single taxa (e.g. Sullivan et al. 2017) or all taxa (e.g. van Horn et al. 2018). Other projects are found in medical fields, informational sciences, and traffic management (Den Broeder et al., 2018; Follett and Strezov, 2015; Gonzalez et al., 2011; Shirk et al., 2012; Wiggins and Crowston, 2011).

3.1.3 Classifications of Citizen Science projects

Projects can be classified according to the level of participant involvement or the focus of project. Participants may only collect data or may be involved in the whole process of devising questions, collecting data, conducting analyses, and sharing results (Conrad and Hilchey, 2011; Gonzalez et al., 2011; Irwin, 2018; McKinley et al., 2017; Miller-Rushing et al., 2012; NASEM, 2018; Silvertown et al., 2013). Bonney et al. (2009a) defined three categories of citizen science based on the level of participation: contributory, collaborative, and co-created. Shirk et al. (2012) defined five models also based on this: contractual, contributory, collaborative, co-created, and collegial. Lawrence (2006) in (Conrad and Hilchey, 2011) organized participation into four forms: consultative, functional, collaborative, and transformative. The definitions for many of these are similar and overlap, but there can also be differences, so it is important to establish the meaning of these terms in publications or when comparing projects.

Wiggins and Crowston (2011) identified five categories which relate to the type of project: socio-political action on local environmental issues; conservation projects, stewardship, and monitoring; real-world scientific investigation of particular questions; virtual scientific investigation of particular questions; and education and outreach. Bell et al. (2008) present the four categories proposed by McKelvey (1975), which relate to the type of organization: participatory environmental tourism; virtual network organisations; national non-governmental organisations; and local associations (Bell et al., 2008). Silvertown (2009) proposed categories of hypothesis-driven research, volunteer mapping and monitoring, and tools, guidance, and resources. Follet and Strezov (2015) initially divided projects into contributory, collaborative, and co-created, and then divided them based on their stated goals, including action, conservation, investigation, virtual and education.

There are pros and cons to all of these classifications, and no one is better overall than another (Conrad and Hilchey, 2011; Shirk et al., 2012). Certain styles of projects may suit some project types or scales better than others. For example, consultative and functional styles work better in large-scale projects that are “top-down” directed, while collaborative and transformative projects work better at smaller scales that are often “bottom-up” directed (Conrad and Hilchey, 2011; Shirk et al., 2012).

3.2 Why have citizen science?

There are many benefits of citizen science to science, participants, policy and management. They are summarized in Figure 1 and discussed below.

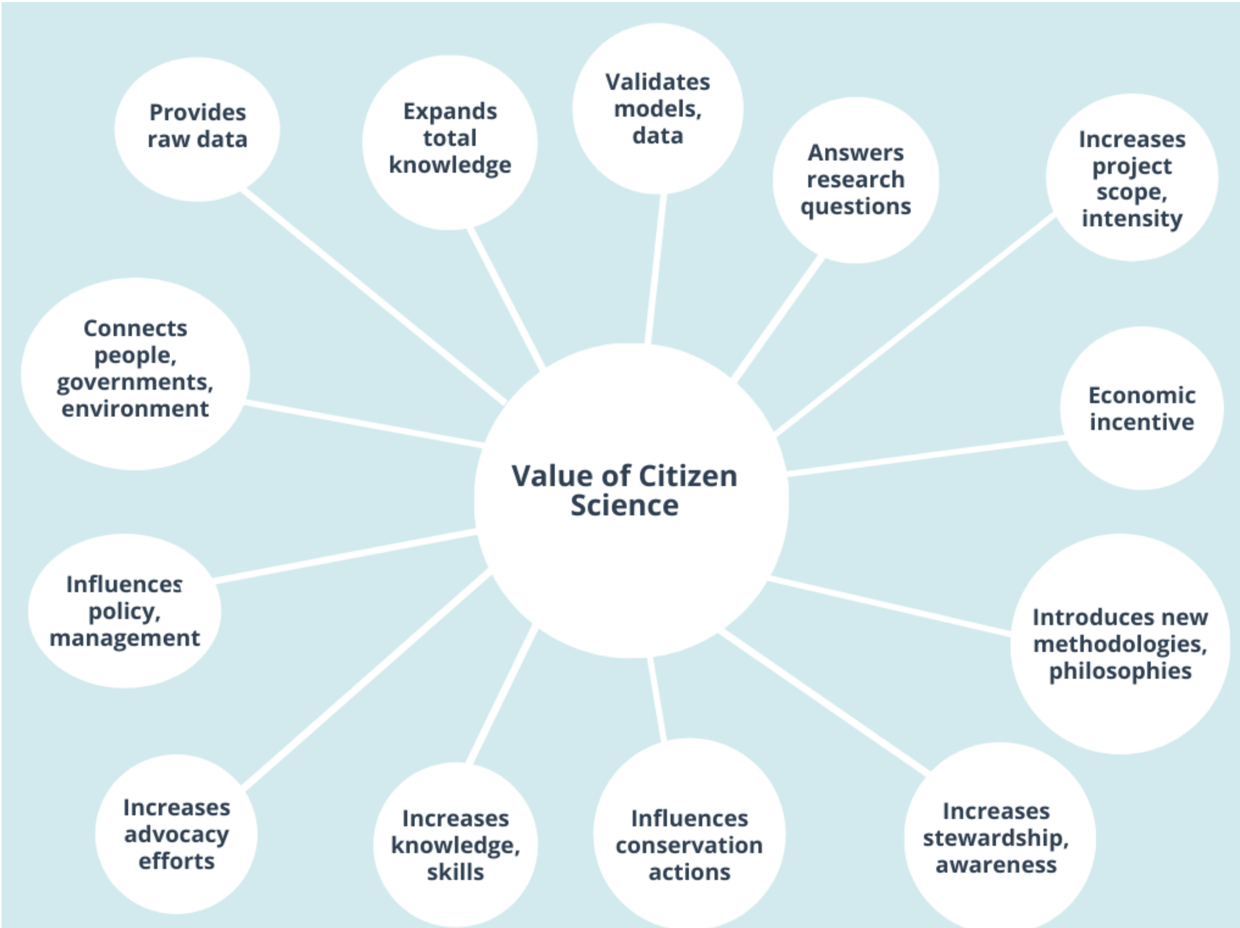

Figure 1. Example values of citizen science.

3.2.1 Value to Science

Citizen science programs can provide ecological data, answer research questions, increase learning, stewardship and awareness, introduce new epistemologies, and influence conservation actions and policies (Conrad and Hilchey, 2011; Follett and Strezov, 2015; Gonzalez et al., 2011; Irwin, 2018; Jordan et al., 2016; McKinley et al., 2017; NASEM, 2018; Peters et al., 2017; Reynolds et al., 2017; Thomas, 2016; Wiggins and Crowston, 2011). In particular, they help answer questions related to the abundance, distribution, behaviour, and changes in species, habitats, and ecosystems (including agricultural systems)(Aceves-Bueno et al., 2017; Acorn, 2017; Eaton et al., 2017; Ryan et al., 2018; Sullivan et al., 2017).

This power comes as volunteers can increase the temporal and spatial scope and intensity of a project, often beyond anything professional scientists could accomplish alone (Acorn, 2017; Bell et al., 2008; Conrad and Hilchey, 2011; Cooper et al., 2012; Danielson et al., 2014; Hoyer et al., 2012; Miller-Rushing et al., 2012; Parker and Thomson, 2018; van der Wal et al., 2015). These data can be of high quality, similar to or identical to that collected by experts (Danielson et al., 2014; Hoyer et al., 2012; Starr et al., 2014; Thomas, 2016; Trautmann et al., 2012; van der Velde et al., 2017), although it depends on the program design and level of skills needed (Acorn, 2017; Jordan et al., 2012; Kremen et al., 2011; Trautmann et al., 2012).

Citizen science data can be added to professional data to fill in gaps and/or expand total knowledge (Bonter et al., 2012; Gonsamo et al., 2013; MacPhail et al., 2019; Silvertown et al., 2013; Soroye et al., 2018; Zapponi et al., 2017; Zuckerberg and McGarigal, 2012). It can be used to validate models (Gonsamo et al., 2013; Pimm et al., 2014) and ground-truth remote sensing data (Cooper et al., 2012; Hannibal, 2016; Pimm et al., 2014). Other projects are concerned with issues of economic, social, and environmental importance (Conrad and Hilchey, 2011; Gonzalez et al., 2011). Other data sets (e.g. environmental, demographic) can be combined with citizen science data to further explore trends and answer questions (Acorn, 2017; Hames et al., 2012).

Projects have the potential to answer questions from changes in range and climate (Bonney and Dickinson, 2012; Bonter et al., 2012; Cooper et al., 2012; Gonsamo et al., 2013; Miller-Rushing et al., 2012; Sullivan et al., 2017) to habitat loss and landscape level analyses (Dickinson and Bonney, 2012; Miller-Rushing et al., 2012; Zuckerberg and McGarigal, 2012) and evaluation of ecosystem goods and services (Birkin and Goulson, 2015). They can track changes in populations over time, including declines of rare species and spread of invasive ones (Acorn, 2017; Dickinson et al., 2012; MacPhail et al., 2019; McKinley et al., 2017; Soroye et al., 2018; Sullivan et al., 2017; Zapponi et al., 2017), as well as migration rates or impacts of predators, disease, pollution, infrastructure, effects of livestock, environmental events, and other human activities (Acorn, 2017; Bonney et al., 2014; Bonter et al., 2012; Conrad and Hilchey, 2011; Cooper et al., 2012; Danielson et al., 2014; Eaton et al., 2017; Greenwood, 2012; Tidball and Krasny, 2012).

Studies can be designed to replicate historic research to evaluate changes over time (Miller-Rushing et al., 2012; Worthington et al., 2012) or provide necessary monitoring to back up claims or evaluate actions (Danielson et al., 2014). They can act as a “crisis response network” (Hannibal, 2016), reacting quickly to monitor changes (e.g. in water or air quality, distribution of pathogens or invasive species) (Bonney et al., 2014; Cooper et al., 2012; Hannibal, 2016; Shirk et al., 2012), while also connecting local people to each other, governments, and the environment, and helping them recover their own livelihoods and landscapes (Dickinson and Bonney, 2012; Owen and Parker, 2019; Tidball and Krasny, 2012).

New technologies provide options to the traditional approach of in-person observations or collections that are shared on paper. For example, images, videos, and other data (e.g. radiation counts) can be obtained by individuals via data loggers, tablets, smartphones, wildlife cameras, satellites, telescopes, and drones and shared over the internet (Acorn, 2017; Austen et al., 2018; Bonney et al., 2014; Eaton et al., 2017; Frigerio et al., 2018; Odenwald, 2019). Data processing can be done by humans and computers, with new techniques evolving all the time (Ceccaroni et al., 2019; Russell, 2014; Shirk et al., 2012; Terry et al., 2020; Wäldchen and Mäder, 2018).

There can be an economic incentive to using citizen science. While there are costs, such as technology needs and staff salaries (Blaney et al., 2016), and recruiting, training, and retaining volunteers (Blaney et al., 2016; McKinley et al., 2017; Silvertown et al., 2013), overall costs are lower than hiring an equivalent number of staff (Joint Nature Conservation Committee, 2017). For example, 100,386 users participated in the first 180 days of seven projects on the broad Zooniverse platform, contributing 129,540 hours estimated at $1.6 million USD (Sauermann and Franzoni, 2015). Theobald et al. (2015) estimated that about 1.3 million citizen scientists contributed $2.5 billion USD in-kind annually over 388 projects. Investments can therefore bring high returns. Indeed, the Joint Nature Conservation Committee (nd, cited in MacKechnie et al. 2011) estimated that a £7 million government investment into volunteer monitoring in 2007-2008 facilitated an in-kind outcome of about £20 million from volunteers. However, citizen science should not entirely replace research by academic or government organizations, particularly as many governments require data to enact parts of their environmental legislation and thus should bear responsibility for the cost and commitment to collect the data (Birkin and Goulson, 2015; Conrad and Hilchey, 2011; Hoyer et al., 2012; Le Féon et al., 2016; MacKechnie et al., 2011; Owen and Parker, 2019; Silvertown, 2009).

3.2.2 Value to Participants

Citizen science can increase awareness, knowledge, and skills, as well as conservation and advocacy efforts among participants and the public (Bubela et al., 2009; Conrad and Hilchey, 2011; Le Féon et al., 2016; McKinley et al., 2017; Miller-Rushing et al., 2012; NASEM, 2018; Socientize Consortium, 2013; Toomey and Domroese, 2013). As we are in an age of increasing environmental degradation and disconnect from nature, public engagement and nature based experiences are key (Acorn, 2017; Conrad and Hilchey, 2011; Hannibal, 2016; Schuttler et al., 2018; Socientize Consortium, 2013).

A person's attitude towards, and knowledge about, the environment can predict and influence their behaviours related to conservation (Bickford et al., 2012; Jordan et al., 2012; Toomey and Domroese, 2013). Participation in citizen science projects can lead to a closer relationship to nature and a greater appreciation of species and their environment (Acorn, 2017; Bickford et al., 2012; Schuttler et al., 2018; Silvertown et al., 2013; Wells and Lekies, 2012). It can also lead to participants becoming experts in the field in the future (Ballard et al., 2017; Hannibal, 2016; Trautmann et al., 2012). But impacts of participation can be short or long lasting (Jordan et al., 2012; Wells and Lekies, 2012), and not all participants report changes in behaviours or actions (Ellwood et al., 2017; Toomey and Domroese, 2013), just as data collection alone does not trigger understanding of scientific processes (Trautmann et al., 2012). Learning is not always an outcome of participation (Bonney et al., 2009a, 2009b; Fitzpatrick, 2012; Jordan et al., 2016, 2012; Phillips et al., 2012), and knowledge does not always lead to an increase in actions (Bickford et al., 2012). Participants may volunteer to enjoy time in nature or with like-minded people, rather than specifically for nature conservation (Bell et al., 2008). However, some participants have expressed major changes in how they act (Bonter et al., 2012; Jordan et al., 2016; Toomey and Domroese, 2013), and any positive change is better than no change (Silvertown et al., 2013).

3.2.2 Value to Policy and Management

Citizen science can influence policy and management actions (Acorn, 2017; Conrad and Hilchey, 2011; Dickinson et al., 2012; Firehock and West, 1995; Greenwood, 2012; Hoyer et al., 2012; McKinley et al., 2017; Peters et al., 2017; Shirk et al., 2012; Socientize Consortium, 2013). However, the impacts of specific projects are often unknown (Acorn, 2017; Harry M. Collins and Evans, 2002; Conrad and Hilchey, 2011; Toomey and Domroese, 2013). More research is needed into the design of projects so that desired outcomes occur (Ballard et al., 2017; Bonney et al., 2014; Socientize Consortium, 2013; Toomey and Domroese, 2013).

3.3. Where can citizen science occur?

Projects can literally occur anywhere in the world, although the United States and Canada have the fastest growing number of programs (Lawrence 2006 in (Conrad and Hilchey, 2011)). Urban environments are well suited (Davies et al., 2011; van der Wal et al., 2015) but activities can happen anywhere: backyards, urban parks, conservation areas, other natural and agricultural areas, or anywhere there is a computer or smart device and internet access (Bonter et al., 2012; EarthWatch, 2018; Griffin Burns and Harasimowicz, 2012; Hannibal, 2016; Khatib et al., 2011; Russell, 2014; Ryan et al., 2018). Projects may be local, provincial/state/territorial, national, or international in scope.

3.4 Who are citizen scientists?

Just as there is no one definition for citizen science, there is no consensus for what a participant is called. There is debate over the term to use, as the language has implications for both volunteer management and knowledge generation (Eitzel et al., 2017). The original use of the term “citizen scientist” has been credited to Rick Bonney at Cornell University in the United States in the mid-1990s (Hannibal, 2016), although Alan Irwin used the term in Europe in 1994 (Follett and Strezov, 2015; Hannibal, 2016; Irwin, 1995).

The very first naturalists can be considered citizen scientists (Bonter et al., 2012; Dickinson and Bonney, 2012; Miller-Rushing et al., 2012; Russell, 2014; Silvertown, 2009). Phenological records date back over three thousand years in China (Bonter et al., 2012; Russell, 2014). Many early naturalists were not professional scientists and conducted their explorations on the side (Bonter et al., 2012; Dickinson and Bonney, 2012; Russell, 2014; Silvertown, 2009). Over time, more individuals were hired as professional researchers, and those who pursued their work as a hobby began to be considered as amateurs (Miller-Rushing et al., 2012; Silvertown, 2009). However, “amateurs” may be well educated, have skills in the area, and even be leading experts in the field (Bell et al., 2008; Bonter et al., 2012; H. M. Collins and Evans, 2002; Miller-Rushing et al., 2012; Shirk et al., 2012).

Citizen scientists today are people who generally volunteer on their own time with scientific projects (Dickinson and Bonney, 2012); they range in their level of expertise, although most projects do not require formal training, credentials, or experience (Acorn, 2017; Danielson et al., 2014; Hannibal, 2016). People of all ages, sexes, and abilities can participate. Age generally does not have an effect on volunteer ability or rate of participation (Ballard et al., 2017; MacPhail et al., 2020; Silvertown et al., 2013), but different ages may be better suited for certain activities (Griffin Burns and Harasimowicz, 2012; Silvertown et al., 2013; van der Velde et al., 2017).

Participants can volunteer individually, with their family, school, or with a group of similar or mixed ages (Ballard et al., 2017; Bonter et al., 2012; Frigerio et al., 2018; Griffin Burns and Harasimowicz, 2012; Trautmann et al., 2012; van der Velde et al., 2017). However, individuals who are the subject or focus of the research project are not citizen scientists (NASEM, 2018).

Generally program participants are not as diverse as they could be, with most being middle-aged or older (MacPhail et al., 2020; Purcell et al., 2012; Toomey and Domroese, 2013), female (Toomey and Domroese, 2013), upper-middle class and white (NASEM, 2018; Purcell et al., 2012). Programs also tend to target and involve groups of avid participants/hobbyists and not the general public (Fitzpatrick, 2012). However technology is allowing citizen science projects to cross cultural, language, literacy, and physical barriers (Bonney et al., 2014; Danielson et al., 2014; Hannibal, 2016; Kawrykow et al., 2012; Khatib et al., 2011; Liebenberg et al., 2017; Russell, 2014).

3.5 Why do citizen scientists participate?

Participants participate for many reasons. Some enjoy the competition to find rare species or more species than others, the ability to survey in areas lacking in data, or to add to their life lists of species (Acorn, 2017; Hannibal, 2016; Prudic et al., 2017; Russell, 2014; Sullivan et al., 2009; van der Wal et al., 2015). Others want to learn about the world around them (Bonter et al., 2012; Shirk et al., 2012; Trautmann et al., 2012; van der Wal et al., 2015; Voss et al., 2017), contribute to our overall knowledge (Dickinson and Bonney, 2012; Shirk et al., 2012; Trautmann et al., 2012), help with conservation efforts (Lewandowski and Oberhauser, 2017; MacPhail et al., 2020; Shirk et al., 2012; van der Wal et al., 2015), gain local knowledge related to a concern in the community (Conrad and Hilchey, 2011; Firehock and West, 1995; Greenwood, 2012; Hannibal, 2016; Miller-Rushing et al., 2012; Roy and Edwards, 2019; Russell, 2014; Shirk et al., 2012) or influence decision making (Conrad and Hilchey, 2011; Shirk et al., 2012).

Many love the social aspect of participating (Bell et al., 2008; NASEM, 2018; Shirk et al., 2012; van der Wal et al., 2015) while others appreciate being alone in nature (Bell et al., 2008). Some participate through school projects (Oberhauser and Lebuhn, 2012; Russell, 2014; Worthington et al., 2012) or to protect their livelihoods ((Danielsen et al. 2007) in (Shirk et al., 2012)). Improving personal skills and abilities is important (Bell et al., 2008; Bonter et al., 2012; Dickinson and Bonney, 2012; Shirk et al., 2012; van der Wal et al., 2015) but so is having fun (Hannibal, 2016; Kawrykow et al., 2012; Khatib et al., 2011; Ponti et al., 2018), and improving their health (Bell et al., 2008; Wells and Lekies, 2012).

3.6 Experimental design, data collection, quality control, and analyses

A variety of experimental designs exist, from one-off collections or incidental observations to formal atlas squares or assigned routes (Acorn, 2017; Bonter et al., 2012; McKinley et al., 2017; Sullivan et al., 2017; Zuckerberg and McGarigal, 2012). Resources for guiding citizen science projects are compiled by the US government (CitizenScience.gov, 2020), Citizen Science Association (2020), California Academy of Sciences (2019), and other organizations (Pocock et al., 2014; Tweddle et al., 2012). There are also specific resources for data management, including ensuring data validation and quality and control assurances are in place (Kelling, 2012; NEIWPCC, 2016; Strasser et al., 2012; USEPA, 2002; Wiggins et al., 2013).

Projects can be designed to answer specific questions or to collect data broadly (Cooper et al., 2012; Hannibal, 2016), but study design must be considered in order for the project's results to be accepted and its impacts measured (Acorn, 2017; Bonney et al., 2009b; Bonney and Dickinson, 2012; Conrad and Hilchey, 2011; Hannibal, 2016; Shirk et al., 2012; Strasser et al., 2012; Wiggins et al., 2013). Project designers must consider the potential participants and their skill levels, and develop training materials and methods to suit (Dickinson and Bonney, 2012; Frigerio et al., 2018).

Project design is often done by professional researchers but can also include, or even be led by, members of the public, stakeholders, and other professionals (Bonter et al., 2012; Conrad and Hilchey, 2011; Cooper et al., 2012; Dickinson and Bonney, 2012; Shirk et al., 2012). Additional members can include individuals experienced in statistics (Bonney and Dickinson, 2012; Cooper et al., 2012; Hannibal, 2016); data management and analyses (Bonney and Dickinson, 2012; Kelling, 2012); computer programming (Ceccaroni et al., 2019; Frigerio et al., 2018; Jordan et al., 2012; Terry et al., 2020; Wäldchen and Mäder, 2018); volunteer management; collective action; and social networking theory (Jordan et al., 2012; Purcell et al., 2012; Triezenberg et al., 2012; Wells and Lekies, 2012).

New statistical and computational techniques are being developed that better compile and analyze complex and unstructured data sets (Acorn, 2017; Bonney et al., 2014; Cooper et al., 2012; Dickinson and Bonney, 2012; Fink and Hochachka, 2012; Gonsamo et al., 2013; Pocock et al., 2015). They can handle "sampling bias, detection, measurement error, identification, and spatial clustering (Bird et al. 2013, Munson et al. 2010)" (Bonney et al., 2014), nonindependence (Cooper et al., 2012), false negatives (Steve Kelling et al., 2015), and various other errors or biases (Acorn, 2017; Fink and Hochachka, 2012; Gonsamo et al., 2013; Johnston et al., 2018). They can also be used for data mining (Fink and Hochachka, 2012) and model validation (Fink and Hochachka, 2012).

Historically, participants mailed paper records to researchers, although most now enter records digitally (Bonter et al., 2012; Purcell et al., 2012). Physical specimens may still be mailed to researchers (Acorn, 2017; Hannibal, 2016; Le Féon et al., 2016), viewed in person (Acorn, 2017), or identified from photos (Acorn, 2017; Blake et al., 2012; Falk et al., 2019; MacPhail et al., 2020; Soroye et al., 2018). Some programs tag animals with the tags later viewed or recovered by other individuals, who then pass the information to the researchers (Acorn, 2017).

Data may be collected in field notebooks (Acorn, 2017), data sheets (Worthington et al., 2012), smart devices (Frigerio et al., 2018; Pimm et al., 2014), or transcribed from historic images or specimens (Acorn, 2017; Cooper et al., 2012; Hannibal, 2016). The information can be e-mailed to the researcher (Acorn, 2017; Hannibal, 2016; Le Féon et al., 2016), entered through an online portal (Blake et al., 2012; MacPhail et al., 2020; Pimm et al., 2014; Silvertown et al., 2015; Toomey and Domroese, 2013; Worthington et al., 2012), shared on and/or culled from social media (Acorn, 2017; Daume and Galaz, 2016; Hannibal, 2016; Russell, 2014; Smith et al., 2017), and photo sharing sites (Hiller and Haelewaters, 2019; Stafford et al., 2010). New technology allows for some data to be automatically recorded and transferred to researchers (Cooper et al., 2012), or identified automatically (Ceccaroni et al., 2019; Terry et al., 2020;

Wäldchen and Mäder, 2018). Not all programs require confirmation of observations, although most have techniques to lower errors in the data (Acorn, 2017; Bonter et al., 2012; S Kelling et al., 2015).

The classical citizen science paradigm has participants collecting the data, including identifying species, and sending it directly to the researchers, while in the expert-assisted paradigm, participants collect materials and send that to the researchers or other experts to identify (Le Féon et al., 2016). Some species groups are well suited for the classical paradigm as they are easy for citizen scientists to identify but others are more difficult (Le Féon et al., 2016). Alternatives include accepting a higher taxonomic level of identification or involving experts, although having enough experts to do the identifications is a challenge (Falk et al., 2019; Kremen et al., 2011; Le Féon et al., 2016; MacPhail et al., 2020). A further challenge is the quality and composition of the photos or specimens submitted (Austen et al., 2018).

The accuracy of participants as compared to experts needs to be considered, as volunteers may have less formal training and/or inherent biases (Austen et al., 2016; Blaney et al., 2016; Danielson et al., 2014; Johnston et al., 2018; Roy and Edwards, 2019; Silvertown et al., 2015; Trautmann et al., 2012). Yet often their ability to identify species is not questioned, and their experience not quantified or accounted for (Acorn, 2017; Austen et al., 2016). Some programs will accept identifications from anyone, others have developed a ranking system that takes into account the individual's skill, and others allow participants to suggest an identification that is verified by experts (Acorn, 2017; Blake et al., 2012; Falk et al., 2019; MacPhail et al., 2020; Silvertown et al., 2015). However, in many cases, citizen scientists can provide accurate data (Acorn, 2017; Austen et al., 2018; Ballard et al., 2017; Bonter et al., 2012; Danielson et al., 2014; Hoyer et al., 2012; Kremen et al., 2011; Lovell et al., 2009). Although the accuracy of the expert is not often questioned, it can be variable (Austen et al., 2018; Suzuki-Ohno et al., 2017).

There can be serious repercussions for misidentifications, such as "the accidental culling of endangered species…(Hunt 2015), the incorrect monitoring of harmful algal blooms (Culverhouse et al. 2013), the unobserved decline in important fish stocks (Beerkircher et al. 2009), and wasted resources,(Solow et al 2012)" (Austen et al., 2016). It can also "affect assessments of population status and distribution and result in erroneous conservation decisions (Elphick 2008, Shea et al. 2011, Runge et al. 2007)" (Austen et al., 2016). It is therefore important to understand the level of potential error during study design and analysis, and when developing conservation actions (Austen et al., 2016). This is particularly true for programs that do not keep photos or specimens (Acorn, 2017; Worthington et al., 2012).

Spatial biases are reflected in e.g. more data coming from densely populated areas than rural areas (Blaney et al., 2016; van der Wal et al., 2015), although this may be balanced by skilled naturalists focusing outside of urban areas and lay individuals inside (van der Wal et al., 2015). Species biases occur through selective reporting, over-reporting, or under-reporting of rare or enigmatic species (Acorn, 2017; Gardiner et al., 2012; S Kelling et al., 2015; Stribling et al., 2008; van der Wal et al., 2015). Temporal biases result from observations occurring more at certain times of the day or year than others (van der Wal et al., 2015). Non-standard search efforts can be sensitive to these biases (Acorn, 2017; Pocock et al., 2015).

Interpretation of data may need to consider the popularity of a program as compared to the number of submissions (e.g. is a species increasing or are more individuals participating)(van der Wal et al., 2015). Researchers also need to consider false positives (reporting a species that is not present) and false negatives (not reporting a species that is present) (S Kelling et al., 2015). Zero data (e.g. absence of a species) is often not collected but is very important (Cooper et al., 2012; Russell, 2014).

Quality assurance and control, and data validation, are important aspects of all programs. Any project has the potential for errors (deliberate or accidental); researchers must attempt to recognize, control, and fix or remove them (MacKechnie et al., 2011; NEIWPCC, 2016; Rasmussen, 2019; Roy and Edwards, 2019; Strasser et al., 2012; USEPA, 2002; Wiggins et al., 2013; Worthington et al., 2012). Some programs may keep erroneous data in user profiles and online maps so as to not hurt the observers feelings; this is concerning and it is important for data users to obtain a good understanding of the data status and background before using (Bonter et al., 2012). Misconduct and incorrect information should be corrected immediately to prevent problems with credibility, data analyses, and funding (Rasmussen, 2019; Roy and Edwards, 2019).

Both current and historic data sets can cover a spectrum of data types, techniques, and levels of participation (Miller-Rushing et al., 2012; Worthington et al., 2012). It is important to review any program documentation to determine the value and quality of the data and how the details may affect analyses (Kelling, 2012; Miller-Rushing et al., 2012; Wiggins et al., 2013).

3.7 Challenges with citizen science

Although there are many positive outcomes of citizen science, there are also challenges and drawbacks (Figure 2). These include issues involving participants, researchers, experimental design and data collection, data use, and the need for specialists. While they may not be unique to citizen science programs, they still should be identified and addressed. Some solutions are discussed in section 3.10.

Figure 2. Example challenges of citizen science.

Barriers related to economics, social status, culture, accessibility, time, language, transportation, plus discrimination, lack of trust, or a perception of science being "boring", may prevent individuals from participating (Acorn, 2017; Birkin and Goulson, 2015; Bonter et al., 2012; Conrad and Hilchey, 2011; Purcell et al., 2012; Worthington et al., 2012). Designing and running a citizen science program can take time away from researcher's professional work and potentially reduce their productivity (Dickinson and Bonney, 2012; Silvertown et al., 2013); early career researchers may not be able to make the necessary commitment (Irwin, 2018). Obtaining adequate funding to start and sustain projects can also be a challenge (Blaney et al., 2016; Bonter et al., 2012; Conrad and Hilchey, 2011; Dickinson and Bonney, 2012; Frigerio et al., 2018; Silvertown, 2009; Silvertown et al., 2013).

Projects may not have a robust experimental design, such as an adequate sample size or a plan to analyze the data (Bonney and Dickinson, 2012; Conrad and Hilchey, 2011). They may collect the wrong type of data or be seen as monitoring for the sake of monitoring (Conrad and Hilchey, 2011; Toomey and Domroese, 2013). With the variation in the types and scope of data being collected, new computer programs and types of analyzes are needed (Bonney and Dickinson, 2012; Ceccaroni et al., 2019; Conrad and Hilchey, 2011; Cooper et al., 2012). Any delays in identifications or analyses can have a negative effect on participant involvement, as well as for end users such as policy makers and conservationists (van der Wal et al., 2015).

Unfortunately, due to concerns related to quality, validity, and consistency of the data and experimental design, results of citizen science programs are not always accepted or used by other researchers, peer-reviewed journals, or decision makers (Burgess et al., 2017; Conrad and Hilchey, 2011; Cooper et al., 2012; Hoyer et al., 2012; Rasmussen, 2019; Silvertown et al., 2013). While Burgess et al. (2017) found that data quality itself was not a strong barrier to researcher use of data, lack of awareness of the data and researcher bias were. These concerns can mean that much-needed data for species conservation status assessments may be excluded, targeted habitat conservation actions may not occur, ongoing environmental issues (e.g. pollution, noise) may not be addressed, models may not be validated correctly, and policy may not be developed. As well, funders of the program may be upset that there were "no" results and be reluctant to fund additional programs in the future, and volunteers may be disheartened by the impression their work was not useful and not participate in the future. Other programs may not be able to learn from or build off the excluded program(s) data. Finally, the discrediting of some citizen science data may put a pall over other programs, negatively influencing their success and impressions.

It is difficult to make broad statements about the impact of citizen science as there is no standardized method of assessment (Bonney et al., 2009a; Conrad and Hilchey, 2011; Jordan et al., 2012; Phillips et al., 2012), although frameworks are being discussed (Bonney et al., 2009a; Ellwood et al., 2017; Jordan et al., 2012; Phillips et al., 2012; Toomey and Domroese, 2013; Wells and Lekies, 2012). Most frameworks are based on those that evaluate public participation in scientific research (Blaney et al., 2016; Phillips et al., 2012; Schröter et al., 2017), while some are specific to children and their environmental attitudes, behaviours, knowledge, and measure of fear (Wells and Lekies, 2012), or specific to informal science education (Bonney et al., 2009a; Phillips et al., 2012). Current methods have trouble evaluating slight changes in knowledge or attitude, particularly when a participant already had experience in an area (Phillips et al., 2012), or to prove that learning was a result of participation (Phillips et al., 2012). It is still important to take pre and post measures in order to evaluate impacts of participation, whether through workshops, online quizzes, or other methods (Phillips et al., 2012; Wells and Lekies, 2012). Participants have different cultural, economic, social, ethnic, and geographic makeup, making analyses even more difficult (Phillips et al., 2012).

While much of science relies on comparison to a control group, it is hard to get unbiased groups for citizen science projects, particularly for randomized control trials (Phillips et al., 2012; Wells and Lekies, 2012). This could potentially be accomplished by having a waiting list of people who may/will participate in the future, with individuals randomly assigned to the wait list and the participation groups (Wells and Lekies, 2012).

There are also areas of research that can not be done by citizen scientists, where professionals are required due to specialized experience, equipment, or other project requirements (Blaney et al., 2016; Fitzpatrick, 2012; Tidball and Krasny, 2012). Professionals may be required to meet regulations, such as with animal handling or health and safety (Buesching & Slade 2012 in (Silvertown et al., 2013)), or site access concerns (Blaney et al., 2016). Finally, some argue that long-term monitoring should only be done by professionals rather than volunteers (Luzar et al. 2011 in (Danielson et al., 2014)).

3.8 Economic, social, and political-economic controversy

Citizen science can provide cost-effective ways for data collection (see discussion above). However, a social and political-economic controversy exists related to the reduction in funding many projects are experiencing or the unequal funding paid to new or high-profile projects (Ancker and Flanagin, 2007; Bonter et al., 2012; Bozeman and Gaughan, 2007; Bubela et al., 2009; Conrad and Hilchey, 2011; Godfray et al., 2015; Hannibal, 2016; Nestle, 2001; Rosenstock and Lee, 2002; Silvertown et al., 2013).

One area of concern is that funding can be cut, only given in the short-term, and/or be vulnerable to loss. Monitoring projects in particular are often not seen to provide a lot of value (Hannibal, 2016; Silvertown et al., 2013). Projects face problems if funding is reduced (Conrad and Hilchey, 2011), as is common with funders that prefer to support new programs, even if longer-running programs produce more valuable data and other outcomes (Blaney et al., 2016; Dickinson and Bonney, 2012). Even if funding is maintained, projects can struggle to meet deliverables and expand (Bonter et al., 2012). However, cutbacks in internal government funding can cause an increase in citizen science, as governments still want, and may even be required by law, to collect data and carry out monitoring (Conrad and Hilchey, 2011; Owen and Parker, 2019); in these cases, they should make funding citizen science a priority (Conrad and Hilchey, 2011).

Funding may come with requirements, such as working with industry partners (Bozeman and Gaughan, 2007). A dependency on private funding and bureaucracy can also limit or decrease public trust (Bubela et al., 2009). In the United States, federal funding is decreasing annually while industry funding is increasing, which brings potential concerns about directions of research and biases (Bozeman and Gaughan, 2007; Rosenstock and Lee, 2002). Funding may come from participants themselves via participation fees or material costs (Bell et al., 2008; Bonter et al., 2012; Chu et al., 2012; EarthWatch, 2018; Silvertown et al., 2013).

Politics and legislation can encourage or discourage citizen science. For example, Wyoming passed a law in 2015 that permitted charging individuals who collect "resource data" on "open lands" as trespassers if they intend to submit that information to the government; the law was amended in 2016 but it is still a discouragement to citizen scientists (Opar, 2017; Pidot, 2015). Wyoming has also pushed to only allow water quality data to be collected by governmental entities or contractors, which would prohibit citizen science (Thuermer, 2020; Wyoming Department of Environmental Quality, 2020). However, the United States government passed legislation in 2017 that explicitly permitted the involvement of crowd sourcing and citizen science activities that furthered the missions of its federal science agencies (United States Government, 2017). The US also assembled an online toolkit to facilitate citizen science (CitizenScience.gov, 2020).

3.9 What is success and how can it be measured?

Individuals, science, and society all benefit from citizen science (Bonney et al., 2014; Irwin, 2018; McKinley et al., 2017; NASEM, 2018; Sharma et al., 2019; Sterling et al., 2017; Sullivan et al., 2017). Outcomes vary depending on why the project was created, how it was designed and data used, and how the volunteers embraced it (Ballard et al., 2017; Bonney et al., 2016; Ellwood et al., 2017; Forrester et al., 2017; NASEM - National Academies of Sciences Engineering and Medicine, 2018; Ponti et al., 2018; Theobald et al., 2015). Quantifiable outcomes include number of individuals involved, data records, website visits, publications, workshops and media articles, (Aceves-Bueno et al., 2017; Bonter et al., 2012; Follett and Strezov, 2015; Gonsamo et al., 2013; Irwin, 2018; Phillips et al., 2012; Shirk et al., 2012; Theobald et al., 2015). Qualitative outcomes include an increase in knowledge or the quality of volunteer involvement (Bonney and Dickinson, 2012; Shirk et al., 2012).

Projects may have vastly different numbers for their metrics of success, often due to the type and longevity of the program, but all be considered equally successful by their organizers. For example, the stand alone, single city Neighbourhood Nestwatch program had at least 12 peer-reviewed publications after about a decade (Bonter et al., 2012), while at least 150 have come from the Cornell Lab of Ornithology, which has been involved in multiple projects globally for about a century (Cornell Lab of Ornithology, 2018). Projects associated with the international Earthwatch organization averaged 6.5 publications and 5.2 contributions to management plans and policies each over a seven year period (Chandler et al., 2017). Other projects may not publish their results in peer-reviewed journals (Follett and Strezov, 2015; Sullivan et al., 2017; Theobald et al., 2015) but in other areas like project newsletters (Follett and Strezov, 2015).

The number of observations submitted to a program also varies. The online Zooniverse platform reports over 12 million daily observations across its programs (Sauermann and Franzoni, 2015), while the international eBird program had more than 300 million observations submitted in the first twelve years of the program, with more than 70 million in 2015 alone (Sullivan et al., 2017). The North American eButterfly receives tens of thousands of observations per year (Prudic et al., 2017), while the UK BeeWatch had 10,000 records submitted and verified in its first three and a half years of operation (van der Wal et al., 2015). The Global Biodiversity Information Facility has estimated that "half of its billions of data points [come] from lay sources [and] that it has supplied data for more than 2,500 peer-reviewed papers in the past ten years" (Irwin, 2018).

Generally only a small fraction of people who express interest in a project participate, and even fewer are high contributors (Andow et al., 2016; Birkin and Goulson, 2015; Domroese and Johnson, 2017; MacPhail et al., 2020; Sauermann and Franzoni, 2015; Wood et al., 2011; Worthington et al., 2012); this seems to be particularly true for projects that are larger in size and/or online, although some projects do have high retention rates (Bonter et al., 2012; McCaffrey, 2005; Sauermann and Franzoni, 2015; Theobald et al., 2015). However, "super volunteers" help to offset overall lower participation rates (Hames et al., 2012; Hannibal, 2016; MacPhail et al., 2020; Sauermann and Franzoni, 2015; Wood et al., 2011). Previous experience by participants may increase the success of data collection (Birkin and Goulson, 2015; Danielson et al., 2014; S Kelling et al., 2015); over time, the learning curve decreases while accuracy and breadth of data increases (Danielson et al., 2014; S Kelling et al., 2015).

Participation can result in an increased understanding of and interest in science (Bonney and Dickinson, 2012; McKinley et al., 2017). It can result in participants becoming resources to be approached by others (conservation professionals, school groups, etc.) (Bonter et al., 2012), or participants asking their own questions, which in turn could be answered by using citizen science data (Dickinson and Bonney, 2012).

3.10 How can citizen science programs be improved?

3.10.1 Study design

As every project has different goals and outcomes, there is no one experimental design that will work for all projects. However, researchers can still use standardized techniques and obtain useable data (Cooper et al., 2012; Shirk et al., 2012). Programs based at regional citizen science societies and related organizations (e.g. citizenscience.gov, citizenscience.org, citizensciencealliance.org, ecsa.citizenscience.net, citizenscience.org.au, and citsci.org), in addition to the peer-reviewed journal on citizen science (theoryandpractice.citizenscienceassociation.org), provide resources to assist others, although additional funding and collaboration with experts would improve them further (Bonney et al., 2014; Ellwood et al., 2017; Russell, 2014).

Repeated sampling at a site is preferred versus one-off observations to better account for site or user effects, distinguish between false positives and negatives, and to evaluate changes over time (Acorn, 2017; Cooper et al., 2012; Hannibal, 2016; Zuckerberg and McGarigal, 2012), although long-term repetition of point in time collections can still help to find new species, range extensions, and other data (Acorn, 2017). A few ways to avoid non-random/unrepresentative data include using a stratified random sampling design or gridding the region of interest; non-random distribution of sampling points can be taken into account for analysis and interpretation (Cooper et al., 2012; Greenwood, 2012). It is important that all areas that need to be surveyed are included in the study (e.g. to compare historically surveyed sites), rather than having an open survey process (van der Wal et al., 2015; Worthington et al., 2012). However, observations that are not from repeated survey sites, including those that are incidental, can still be used and can be quite valuable (Gazdic and Groom, 2019; Hochachka et al., 2012; MacPhail et al., 2019; Meiners et al., 2020; Mueller et al., 2019; Sullivan et al., 2017; Wilson et al., 2020; Zapponi et al., 2017).

Projects must encourage the submission of zero data (Cooper et al., 2012; Russell, 2014) and the recording of search effort, as this can help researchers identify undersampled or oversampled areas or quantify variability in data (Zuckerberg and McGarigal, 2012). Where possible, the project should be set up so that data analyses can include observer skill as a factor (S Kelling et al., 2015). Researchers should choose the best species to monitor that will both fit with the research question and be as easy as possible for participants to identify and engage with (Danielson et al., 2014; Worthington et al., 2012).

Pilot studies can help ensure training materials are understood, data is collected efficiently and accurately, participants are engaged in the program, feedback can be addressed, and data can be analyzed (Birkin and Goulson, 2015; Bonney and Dickinson, 2012; Bonter et al., 2012; Frigerio et al., 2018; Greenwood, 2012; Jordan et al., 2012; Shirk et al., 2012; Worthington et al., 2012). It is important to allow for uncertainly to be acknowledged during data recording or verification

(Purcell et al., 2012). Researchers need to determine how to verify records during project design, such as through the submission of photos and not just text (Worthington et al., 2012).

Standardized terminology, classification codes, and methods of recording and entering data can reduce many errors (Greenwood, 2012; Kelling, 2012; Wiggins et al., 2013). Multiple individuals can also assess the same record to ensure agreement (Russell, 2014). Data can be flagged automatically if they fail pre-set criteria (e.g. spatial, temporal, numerical) or a quality assurance test (Bonter et al., 2012; Kelling, 2012; Russell, 2014; Silvertown et al., 2013), although this latter approach does not catch records that are plausible but incorrect (Bonter et al., 2012). It is best if information can be georeferenced to a precise area, whether it be through GPS units, geocoding based on street addresses, selection of a site through online mapping programs, or other methods, as this may allow for multiple uses of the data, including for habitat and landscape level analyses (Zuckerberg and McGarigal, 2012).

Project leaders need to identify learning goals before starting, and design protocols that will result in them, realizing that different approaches may be needed for volunteers than traditional ones used with experts (Jordan et al., 2012; NASEM, 2018; Strasser et al., 2012; Wiggins et al., 2013). For retention to be high, projects should meet the needs of the participants and communities involved; researchers need to have someone who can relate to the community and understand their concerns/biases/strengths (Purcell et al., 2012; Trautmann et al., 2012).

It is important to assess the value and viability of projects at all stages. Blaney et al. (2016) discus four methods, including Return On Investment (values based on financial aspects alone), Cost-Benefit Analysis (values to society, including monetary and non-monetary ones), Cost-Effectiveness Analysis (monetary costs of citizen science as compared to different options), and Multi-Criteria Analysis (comparing value of different options using monetary and non-monetary costs). As more organizations undertake these evaluations, more evidence can be gathered to support current and future investment in citizen science projects.

3.10.2 Volunteer recruitment, training, support, retention

Individuals react differently to recruitment materials depending on their age, national or cultural identity, societal class, and educational background (Silvertown et al., 2013). They also have different motivations for volunteering, from wanting to learn new skills to making a difference in their community to feeling a sense of power (Bonney and Dickinson, 2012; Chu et al., 2012; Domroese and Johnson, 2017; MacPhail et al., 2020; Silvertown et al., 2013). Therefore programs must develop specific messages and use different communication channels, depending on the group(s) they wish to target, rather than one message for a general audience (Bonney and Dickinson, 2012; Chu et al., 2012; Silvertown et al., 2013; Worthington et al., 2012). Wymer (2003) in (Chu et al., 2012) suggests that volunteers be considered as customers, and similar principles considered and actions taken as done by businesses in finding and retaining new customers.

Communications should be made locally relevant, even if part of a broader project (Chu et al., 2012). Messaging should reinforce reasons for and positive outcomes of participation, such as by announcing a data gap in a specific region and the need for people to submit information (van der Wal et al., 2015), or by promoting the health and wellness benefits of participating (Chu et al., 2012), while also linking the scientific and conservation angles (Chu et al., 2012). Communications can also tie into specific events (Worthington et al., 2012), and contests and promotions can increase media attention and recruit new people to a project (Chu et al., 2012).

Barriers to participation must be considered and avoided where possible. For example, a required payment for participation may be prohibitive (Bell et al., 2008; Bonter et al., 2012; Silvertown et al., 2013). Projects that have support and training materials in multiple languages, or heavily rely on graphics versus written text, can reach more people (Liebenberg et al., 2017; Purcell et al., 2012; Worthington et al., 2012). However projects may unconsciously exclude certain minority or underrepresented groups (NASEM, 2018; Purcell et al., 2012). Project organizers must ensure projects are inclusive, equitable, and diverse (NASEM, 2018). Partnerships with other organizations can help researchers reach niche communities or underserved audiences (Chu et al., 2012; Purcell et al., 2012; Silvertown et al., 2013).

Youth involvement is also encouraged as involvement as a youth translates into involvement as an adult, and there is a concern that the current majority of volunteers may soon no longer participate due to age (Wells and Lekies, 2012). As well, there is a need to get more families and children out into the natural world "to know it and care for it" (Dickinson and Bonney, 2012), and "build their capacity for future conservation actions" (Ballard et al., 2017).

Researchers should encourage people to recruit others with whom they rarely interact with in order to bring more people in and move away from "preaching to the choir" approach (Triezenberg et al., 2012). These weak-tie relationships may help spread new information faster than close-tie/strong-tie relationships, although the latter can help to reinforce and foster adoptions of new behaviours (Triezenberg et al., 2012).

Creating tools of value to participants, like the ability to view their own data online and to explore data submitted by other participants, as well as customized data portals for specific projects or areas, can help lead to increased participant involvement (Acorn, 2017; Chu et al., 2012; Prudic et al., 2017). However, more research is needed to understand why some people contribute to projects while others "free ride" on contributed data (Triezenberg et al., 2012).

Advertising can be done through a variety of channels, including social media (Birkin and Goulson, 2015; Chu et al., 2012; Liberatore et al., 2018), blogs, YouTube, RSS feed (Chu et al., 2012), websites (Bell et al., 2008; Birkin and Goulson, 2015; Bonter et al., 2012; Toomey and Domroese, 2013), e-mail listservs (Bonter et al., 2012; Toomey and Domroese, 2013), newsletters (Birkin and Goulson, 2015; Bonter et al., 2012), presentations, flyers (Bonter et al., 2012; Chu et al., 2012), special events (Toomey and Domroese, 2013), conferences (Worthington et al., 2012), other organizations (Bonter et al., 2012; Jordan et al., 2012; Wells and Lekies, 2012), and traditional print and broadcast media (Bell et al., 2008; Bonter et al., 2012; Chu et al., 2012; Silvertown et al., 2013; Toomey and Domroese, 2013; van der Wal et al., 2015; Worthington et al., 2012). However, while media can increase awareness of a project, it may not always result in large numbers of volunteers (Silvertown et al., 2013) or it can recruit too many people, overwhelming the program organizers (Bell et al., 2008). It may be necessary to target publicity to groups that are more likely to participate in order to increase recruitment (Worthington et al., 2012).

Volunteers can be trained in program protocols through a variety of methods. Static training and support documents can be mailed out physically or electronically (Birkin and Goulson, 2015; Bonter et al., 2012; Firehock and West, 1995; Shirk et al., 2012) or resources can be made available online (Birkin and Goulson, 2015; Bonter et al., 2012; Purcell et al., 2012; Shirk et al., 2012; Toomey and Domroese, 2013; Worthington et al., 2012). Participants can carry out simulations of data collection tasks and get feedback, helping them to improve their skills (Bonney and Dickinson, 2012; Jordan et al., 2012; Worthington et al., 2012) while giving researchers the opportunity to evaluate their skill level and potential biases (Dickinson et al. 2010 in (Dickinson and Bonney, 2012)).

Workshops or trainings are often held in-person, varying from a few hours to several days in length (Bonney and Dickinson, 2012; Bonter et al., 2012; Danielson et al., 2014; Hames et al., 2012; Hannibal, 2016; Jordan et al., 2012; Kremen et al., 2011; Le Féon et al., 2016; Silvertown et al., 2013; Toomey and Domroese, 2013). Volunteer accuracy has been shown to increase if training is provided in-person with an expert as compared to just online or mailed materials (Silvertown et al. 2013). Multiple trainings held over time can allow for people to process instructions, build on knowledge, gain experience with the protocols, and avoid information overload (Jordan et al., 2012; Silvertown et al., 2013; Trautmann et al., 2012). Training should be provided on recognizing and avoiding biases, and the consequences of not doing so (Jordan et al., 2012; Silvertown et al., 2013).

It is important that participants can connect with project leaders. Some programs provide a phone number for participants to call with questions or problems (Birkin and Goulson, 2015; Bonter et al., 2012; Firehock and West, 1995; Purcell et al., 2012; Shirk et al., 2012), while others regularly correspond by e-mail (Bonter et al., 2012; Chu et al., 2012; Purcell et al., 2012; Toomey and Domroese, 2013), and others have participants and researchers meet up periodically during the year (Bonter et al., 2012; Danielson et al., 2014; Hames et al., 2012; Hannibal, 2016). Support and information sharing can come from both researchers and participants through online discussion forums, blogs, and social networking tools (Bonney and Dickinson, 2012; Bonter et al., 2012; Daume and Galaz, 2016; Liberatore et al., 2018; Toomey and Domroese, 2013; Triezenberg et al., 2012). Small programs with more interactions with researchers, particularly in-person, may yield more impact on participants and greater change in their behaviour, knowledge, and actions than programs with solely online training or single workshops (Bonter et al., 2012). More research is needed to understand how virtual communications and trainings work to connect people and create a sense of community (Liberatore et al., 2018; Triezenberg et al., 2012).

An important aspect of project management involves participant retention, as this decreases initial training and recruitment costs, builds expertise, and increases data quality (Bonter et al., 2012). In addition to regular communications, volunteers want to receive feedback on and be recognized for their efforts, have their motivations for participating met, and have a rewarding experience (Acorn, 2017; Chu et al., 2012; Conrad and Hilchey, 2011; Fitzpatrick, 2012; Greenwood, 2012; NASEM, 2018; Prudic et al., 2017; Purcell et al., 2012; Silvertown et al., 2013). Too often programs are just about getting the data, leaving the participants feeling undesired and unappreciated (Silvertown, 2009).

Feedback can be automatically sent to volunteers after data is submitted or verified (Russell, 2014; Silvertown, 2009; van der Wal et al., 2016, 2015; Worthington et al., 2012), while interactive websites can display their data live and compare it to other data on maps or to past records by the participant (Bonney and Dickinson, 2012; Bonter et al., 2012; Chu et al., 2012; Dickinson and Bonney, 2012; Sullivan et al., 2009). Participant spotlights can be placed online or in newsletters (Chu et al., 2012). A general acknowledgement of volunteers can occur in the media directly, and by sharing results showing the value of their work (Bell et al., 2008; Silvertown et al., 2013; van der Wal et al., 2015).

Social interactions and a feeling of community with other volunteers and project leaders, whether done in person or electronically, are important to keep people interested and engaged (Bell et al., 2008; Bonter et al., 2012; Hames et al., 2012; Hannibal, 2016; NASEM, 2018; Shirk et al., 2012; Silvertown et al., 2013; Triezenberg et al., 2012). Some programs are small and locally based or have regional branches that can provide a more local connection and targeted information to participants (Bell et al., 2008; Greenwood, 2012). Informal mentorship between more experienced and inexperienced participants can be quite valuable, even with larger programs (Bell et al., 2008). Concerted efforts to communicate with past and present participants and targeted groups can help to regain and increase participation over time even after the initial wave of enthusiasm for a project has passed (Chu et al., 2012).

It is important for citizen science programs to capture the interest of “super volunteers” and engage and support them (Hannibal, 2016; Silvertown et al., 2013). They could be encouraged to write articles about their participation to be published in newsletters or online (Trautmann et al., 2012), recruited for more in-depth research projects (Cooper et al., 2012; Hames et al., 2012), and encouraged to present at program events or scientific conferences (Trautmann et al., 2012).

Monitoring can be boring and repetitive, leading to carelessness and lower quality data (Hannibal, 2016; Russell, 2014; Silvertown et al., 2013). The best participants are those who are dedicated to a particular site and are attuned to small changes (Hannibal, 2016; Purcell et al., 2012; Russell, 2014). Successful programs may tie into the participants main interests and skills (Conrad and Hilchey, 2011), livelihoods, regular routines, or to their cultural or spiritual values (Danielson et al., 2014) or their motivations (Chu et al., 2012; NASEM, 2018).

Projects vary in the type of equipment required. Some projects are only online, requiring users to have a computer and internet access to participate (Hannibal, 2016; Khatib et al., 2011; Russell, 2014; van der Wal et al., 2015). Others have the user collect data in the field and then enter it online (Birkin and Goulson, 2015; Bonter et al., 2012; Gonsamo et al., 2013; Jordan et al., 2012; Starr et al., 2014), although sometimes the data are mailed back to the researchers (Acorn, 2017). Participants may be provided with specific items, (Birkin and Goulson, 2015; Jordan et al., 2012; Le Féon et al., 2016) although participants may still need to supply some items (Birkin and Goulson, 2015). The creation and use of localized species lists and field guides can make identifications easier for novices as compared to the more traditional regional or continental guides (Silvertown, 2009).

3.10.3 Data management, security, longevity

Thought must be given to the life cycle of data, particularly for the long term use, reuse, and preservation of the data (Kelling, 2012; Strasser et al., 2012; USEPA, 2002; Wiggins et al., 2013). Funders are increasingly requiring data management plans (Kelling, 2012) and as citizen science data are essentially public data, they should be housed in a permanent collection (Kelling, 2012). It is important to be able to combine project data with other data sets, and plan for their use in the future (Greenwood, 2012; Hannibal, 2016; Wiggins et al., 2013), showing the need for common frameworks and data standards (McKinley et al., 2017).

Data should be stored in a database management system as this allows access to multiple individuals at once and can link and analyze large quantities of related information in a systematic way (Cooper et al., 2012; Kelling, 2012). This system is different from a spreadsheet program, which is prone to increasing errors or loss of data due to researcher error (Kelling, 2012). Database programs can be tied to GIS applications (Cooper et al., 2012), and can be handle data from single or multiple projects (Kelling, 2012). Citizen science programs could often support a common database structure (Bonney and Dickinson, 2012; Kelling, 2012; Worthington et al., 2012), although some program databases will still need to be custom built (Worthington et al., 2012), and success relates to the quality of the database cyber-architecture itself (Newman et al. 2011 in (Acorn, 2017), (Bonney and Dickinson, 2012)).

Metadata, or information about the methods used to gather the data, must be developed and associated with the data (Kelling, 2012; Strasser et al., 2012; Wiggins et al., 2013). It is usually in a standardized format, with two interchangeable standards recommended for citizen science: the Biological Data Profile, developed by the Federal Geographic Data Committee (FGDC), and the Ecological Markup Language, developed by the ecological community based on the FGDC standard (Kelling, 2012).

Data must be protected through multiple secure backups (Acorn, 2017; Bonney and Dickinson, 2012; Wiggins et al., 2013). It should also be archived, which is the process of storing data together with the metadata in a long-term storage device (Kelling, 2012; Wiggins et al., 2013). It is important to maintain access to the database, even if or after the project has ended (Acorn, 2017). The Cornell Lab of Ornithology has a comprehensive backup and archival process for their data (Kelling, 2012):

> *"First, every month each database is backed up in its entirely, initially to locally running disks and then off-site to a tape/disk backup system. Any and all changes made to the database are also simultaneously written locally to "change logs" on two different disk volumes. The logs are copied to the off-site system every four hours, and because they grow quickly (currently more than 13 GB/day), once or twice each week they are packaged into "incremental backups" and copied off-site. Therefore even if the database machine suffered a complete loss, only the most recent four hours of user data activity would be irretrievable. Finally, we perform database restoration exercises several times each year to simulate total loss of the database machine. These exercises prove the viability of the backups, improve our restore procedures, and prepare us for an actual restore."* (Kelling, 2012)

Prior to a program starting, policies should be developed about data sharing and management, on topics like intellectual property and open access of data, and to outline any legal or liability considerations (Heigl et al., 2019; McKinley et al., 2017; Strasser et al., 2012; Sullivan et al., 2017; Wiggins et al., 2013). Finally, data privacy and confidentiality must be maintained, especially when data are being shared or presented (Heigl et al., 2019; McKinley et al., 2017; Wiggins et al., 2013). This can range from anonymizing data to using locked or password protected storage devices (Wiggins et al., 2013).

3.10.4 Data awareness, sharing and project overlap

Visibility of citizen science programs, and the existence of their data, needs to be increased amongst scientists to increase the data usage; data should be made widely available, and be frequently shared with national or international repositories (Acorn, 2017; Burgess et al., 2017; Heigl et al., 2019; Hochachka et al., 2012; MacPhail et al., 2020; McKinley et al., 2017; Strasser et al., 2012; Sullivan et al., 2017; van der Wal et al., 2015; Wiggins et al., 2013). Projects should be evaluated and the outcomes (both positive and negative) shared to allow others to use it as a model or to improve similar projects; to add to our knowledge of ecosystem function; and to contribute to socio-ecological topics (Blaney et al., 2016; Bonney and Dickinson, 2012; Conrad and Hilchey, 2011; Gonsamo et al., 2013).

It is important to keep participants informed as to the study's progress and results (Bonney and Dickinson, 2012; MacKechnie et al., 2011). However, participants should be informed from the outset that some questions may take multiple years of data to understand/analyze (Bonney and Dickinson, 2012; Frigerio et al., 2018). Updates and results should be shared with other target audiences, such as landowners, conservation partners, and managers (Bonney et al., 2014; Bonney and Dickinson, 2012; Frigerio et al., 2018). While results should be published in academic, peer-reviewed papers, they must also be provided in formats that participants and other stakeholders can access and understand (Bonney and Dickinson, 2012). Online availability makes it easy for others to access and analyze the data and further increase its reach and value (Bonter et al., 2012; Follett and Strezov, 2015; Hannibal, 2016; Silvertown, 2009; Trautmann et al., 2012; van der Wal et al., 2015). It can also help move citizen science projects along the spectrum from having participants just collecting data to them analyzing the patterns (Hannibal, 2016).

There are pros and cons to the collecting of data or projects under a larger group's umbrella. For example, some smaller grass-roots projects may be best left on their own while others may be taken over by a larger program, particularly if they have more support/resources (Acorn 2017). If data from one project are fed into another, participants need to decide what program to submit their data to, and may decide to bypass the smaller program in favor of going directly to the larger one (Acorn 2017). But by one group supporting smaller groups, they may be able to recruit and support the participants and researchers (Acorn 2017).

It is also important to avoid duplication of efforts. There can be multiple programs in the same area collecting similar data, which can confuse potential participants and/or result in patchy data (Bonney et al., 2014; Bonter et al., 2012; Russell, 2014). Data collection should be standardized across programs, even if there are additional specific questions, and incorporated into one database (Bonney et al., 2014; Bonter et al., 2012; Russell, 2014).

3.10.5 Increased funding and paid staff

Even with the use of volunteers, programs often struggle with getting enough funds to manage their project. But it is important to consider human resources costs for projects; a paid project leader and/or assistants can greatly increase program success (Bonter et al., 2012; Chu et al., 2012; Greenwood, 2012; Worthington et al., 2012). Assistants can help with project planning, recruitment, promotion, mediation, analyses, and evaluation; respond to participant questions and comments; allow for more projects to be launched; and generally take pressure off the main project leaders (Bonter et al., 2012; Chu et al., 2012; Greenwood, 2012; Worthington et al., 2012). Additionally, the cost to hire or provide honoraria to experts (e.g. for identification services) must be considered in budgets (Le Féon et al., 2016). As discussed earlier, it is important to evaluate the monetary and non-monetary values of projects at all stages (Blaney et al., 2016), which by necessity will take into account expenses in addition to outcomes.

4. Conclusion

While scientific research has been carried out by unpaid individuals for centuries, citizen science as a field is relatively new, increasing in popularity over the last few decades. It allows individuals of various backgrounds and skill levels to develop and/or participate in programs collecting information about the world around them, increasing their knowledge, and potentially changing their behaviours related to conservation. Vast quantities of data are now available to help address research questions that would not otherwise be possible without these participants, which in turn help to inform policy and management decisions. The development of new technologies, particularly computers, smart phones, and high-speed internet, are increasing the depth and breadth of data being collected, and the diversity of volunteers who can participate. New experimental designs, databases, and statistical analyses, and common definitions, frameworks and data standards, are being developed to help collect and process new data alone and in conjunction with historic data, as well as store it securely and allow for sharing amongst participants, stakeholders, and other interested parties.

However, challenges do exist. It can be difficult to recruit and retain a diverse group of participants. Projects must be carefully and frequently evaluated and adapted as necessary. Researchers may need to gain experience in new disciplines of work, while juggling volunteer management and communication and their basic research, although having dedicated individuals to assist can help. As with any project, but especially with those using large numbers of volunteers, data collection can be patchy, incomplete, or include errors. Similarly, funding can be difficult to obtain, particularly for longer-term studies, and has a high potential for social-economic or political controversy. In some cases, citizen science data is not recognized or used by other researchers or decision makers, and it can be hard to truly evaluate the outcomes and impacts of a project. Additionally, small-scale programs, or larger-scale programs with patchy participation, may not generate the information needed to answer pressing questions, particularly related to conservation in changing times.

There are still areas where more research is needed, technological through social, and interdisciplinary teams must be put together when developing and running citizen science programs. Insights need to be shared and results (both positive and negative) communicated widely through the citizen science community, the broader scientific ones, and the public. But the potential is there for even further involvement and growth of citizen science programs, to the value of human societies and healthy ecosystems around the world.

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Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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