Quantitative Plant Biology

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Review

Cite this article: A. Receveur et al. Citizen science: How to extend reciprocal benefits from the project community to the broader socio-ecological system. *Quantitative Plant Biology*, **3:**e20, 1–11
https://dx.doi.org/10.1017/qpb.2022.16

Received: 24 June 2021
Revised: 13 June 2022
Accepted: 24 August 2022

Keywords:
big data; citizen science; involvement; quantitative data; socio-ecological system.

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Citizen science: How to extend reciprocal benefits from the project community to the broader socio-ecological system

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Abstract

Quantitative plant biology is a growing field, thanks to the substantial progress of models and artificial intelligence dealing with big data. However, collecting large enough datasets is not always straightforward. The citizen science approach can multiply the workforce, hence helping the researchers with data collection and analysis, while also facilitating the spread of scientific knowledge and methods to volunteers. The reciprocal benefits go far beyond the project community: By empowering volunteers and increasing the robustness of scientific results, the scientific method spreads to the socio-ecological scale. This review aims to demonstrate that citizen science has a huge potential (i) for science with the development of different tools to collect and analyse much larger datasets, (ii) for volunteers by increasing their involvement in the project governance and (iii) for the socio-ecological system by increasing the share of the knowledge, thanks to a cascade effect and the help of 'facilitators'.

1. Introduction

Crowther et al. (2015) estimated that there are 3.04 trillion, or 3.04×10^{18} ($\pm 0.096 \times 10^{18}$), trees worldwide. Although this is an impressive number, it raises a question: How did the scientific team count all the trees on the planet? To better reflect reality, researchers need to collect and treat a huge amount of data sampled in contrasting ecosystems and environmental conditions, which is the role of quantitative plant science (Autran et al., 2021). However, a research team alone is limited in the amount of work necessary to reach a robust and valid result. International collaborations are part of the answer to overcome the lack of data, but this is insufficient and often not representative of the whole data and ecological diversity.

Citizen science (CS) is one way to cover large temporal and spatial scales for sampling. CS is a broad concept, and the definition is still debated (Heigl et al., 2019). We will merely refer to the general definition of Guerrini et al. (2018): CS gathers '*scientific endeavours in which individuals without specific scientific training participate as volunteers in one or more activities relevant to the research process other than (or in addition to) allowing personal data or specimens to be collected from them*'. Even if CS projects that are solely based on data collection may partially solve some quantitative plant science challenges (data collection on large areas, at high temporal resolution, higher number of collectors who may quantify variables more often than a scientific team alone), they also require important scientific input to improve their own modelling issues, such as accounting for bias in data collection and heterogeneity in plant species, sites and/or dates of measurements, and ensuring that the protocol was accurately followed. CS projects in plant sciences have bloomed for a decade, gathering huge volunteer communities around scientific questions (Fig. 1, grey points). The number of publications related to CS projects has increased even faster than the total number of publications in plant sciences (Fig. 1, green bars).

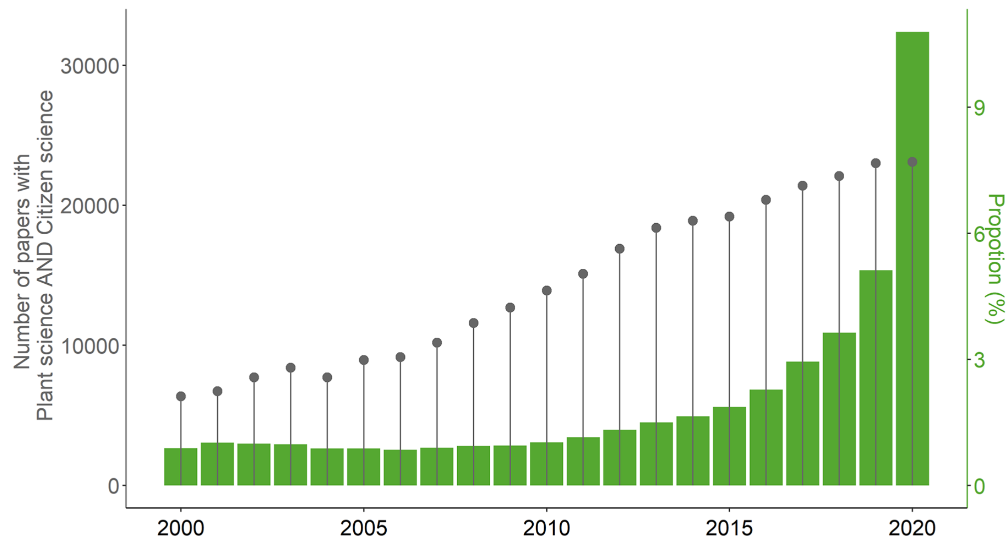

Fig. 1. Global trend of citizen science projects in the plant science literature from 2000 to 2020: The left grey y-axis (grey dots) represents the number of articles containing the mention 'plant science' AND 'citizen science' in their title, and the right green y-axis (green bars) represents the ratio of paper numbers with 'plant science' AND 'citizen science' and the paper numbers containing 'plant science' only. The number of papers was extracted from Google Scholar on 01/02/2022.

In turn, this approach allows researchers to share their experience, method and the purpose of the experiment and to directly communicate them to participants. In that sense, CS projects can be seen as collaborative work with a purely scientific interest to answer a question and as an efficient outreach action where 'non-researchers' are truly active and have the opportunity to practice the sciences (Heigl et al., 2019).

The benefits of these close and direct interactions between scientists and volunteers are not limited to the scientific sphere and/or the volunteers. Mixing scientists and volunteers, CS can be seen as a motor of complex socio-ecological systems, strengthening the interaction network between society and the environment. CS represents an efficient approach linking knowledge creation and transfer/co-construction with society (Rupprecht et al., 2020). The benefits of CS projects spread much further than the scientists–volunteers' interactions, and they also reach the socio-ecological system if the project is built as a participatory action research project (Cooper et al., 2007). Quantitative plant ecology can play a major role in encouraging these collaborative sciences. We chose to broaden the scope of this review from plant science to plant ecology and its quantitative aspect.

The goal of this review is to highlight (i) the diversity of tools and networks enabling scientists to run CS projects, (ii) the reciprocal benefits of CS projects between citizens, the scientific community and beyond with the socio-ecosystem and (iii) some remaining obstacles, such as the need to include a 'facilitator' in volunteer–scientist relationships; finally, this review (iv) proposes some perspectives for upcoming CS projects.

2. Some CS tools encouraging participation in CS projects

2.1. Plant CS project, a mean to manipulate plant

Plant science is mainly based on trait measurement to explain plants' trait response to a tested variable (Autran et al., 2021). The number of replicates is crucial to make the study quantitative and the lab facilities are often limiting as plant culture or field experiment needs space and time. Increasing the number of experimenters may help to solve this issue. Participating to this measurement campaign may be source of motivation for volunteers to engage in CS project and to bring their contribution to the study. Projects including trait measurements allow a direct contact with plant science tools and plant material, which represent a data collection activity very close to the scientific work in a lab. McDonough MacKenzie et al. (2020) described the great interest to engage volunteers in projects including traits' measurement such as flower phenology; volunteers only need a pencil and a sheet to note their observation regularly. These data may be complementary to dataset at global scale gathering observations at larger scale and with experiments such as twig cutting to assess season effect on leafing-out time (McDonough MacKenzie et al., 2020; Primack et al., 2015). Moreover, herbaria data and metadata (from label) may also help to increase the phenology legacy of a species (Funk, 2003; Nualart et al., 2017). Extracting and implementing a database are very time consuming; therefore, herbarium may solicit the volunteer's help to treat each specimen, which what Recolnat or Nature's Notebook programs propose in France and in the USA, respectively, for instance.

Plant's traits variation to environmental changes can be studied in a common garden where different species, genotype, cultivars are grown with the same condition. The number of common gardens limits the number of tested environments. The project '1000 gardens – the soybean experiment' benefited from 1000 gardens of volunteers to grow 1710 soybean lines (Würschum et al., 2019). Participants received 10 lines or varieties and 16 traits were measured by participant until the harvest such as germination rate, plant height and start of flowering. This project led the scientist to know the most adapted lines for the different Germany regions for future soybean production (Würschum et al., 2019). Similarly, a CS project focused on carrot, solicited farmers to assess intraspecific foliar trait variation in Canada. Each farmer was in charge of five varieties of carrot and to collect and send dry leaf samples to the scientific teams for trait's measurement. Even if farmers did not participate to trait measurements, they allow to test different environment to estimate the intraspecific variability of leaf trait (Isaac & Martin, 2019). This collaborative CS project leads to closer relationship between research and farms without excessive cost or particular technology.

However, the development of connected tool facilitates data sharing and data availability, which can help to democratize CS participation.

2.2. Make the CS project more global

The tool diversity in CS projects has increased with the number of projects developed. Smartphones are certainly the best example of making collaborative and quantitative sciences an almost 'common' activity (Adriaens et al., 2015; Newman et al., 2012; Teacher et al., 2013). The smartphone is useful and promising, especially for quantitative plant science, as it allows high-resolution phenotyping activity to supply deep learning techniques and monitor plants' responses to stress and diseases (Mohanty et al., 2016; Singh et al., 2018). For instance, Adriaens et al. (2015) reported two applications RINSE and KORINA to record and monitor invasive plant species: volunteers can record the localisation of invasive species with their apps. Their data are then used by scientists and managers to monitor wetlands. However, volunteer participation in a CS program strongly depends on the ease of using the tools, since volunteers can become discouraged if the tools are too difficult to use. Once the tools are available, the research community can rely on a large pool of potential volunteers among social networks (Serret et al., 2019). The connected tools play an important role in creating a dynamic and virtuous loop among volunteers and an easy way to interact with scientists (Nov et al., 2014), especially if face-to-face interactions with the research team are organised concomitantly (Cappa et al., 2016). We acknowledge that it may be particularly difficult for the scientific team to interact directly with each volunteer, especially in projects involving hundreds or thousands of participants. This challenge clearly shows the need for intermediaries to avoid losing volunteer motivation and the quantitative benefit of volunteer work (Cappa et al., 2016). Some data, such as geolocation, can be updated and visualised by all the project participants directly after the data are collected and incremented. This may represent a tangible, encouraging reward for volunteers and may motivate them to continue working on the project. Moreover, from a research point of view, collected plant-related data may be used with other datasets, such as meteorological and climate data, increasing the power of the collected data. A recent study showed that from crowd-sourced flower identification data, it was possible to rebuild spatial macroecological gradients (Mahecha et al., 2021). This means that we can potentially extract more information than the app was initially designed to deliver.

The almost global internet access allows an instantaneous sharing of data and facilitates their verification by scientists or volunteers (Deguines et al., 2018); hence, it makes data quantity compatible with data quality. However, while the size of the available datasets is growing very fast (e.g., satellite images, video recording, pictures, for instance https://www.zooniverse.org/projects/zooniverse/floating-forests: 750,000 pictures of kelp forests were classified by over 7000 volunteers), the number of scientists available to analyse these data is not growing as fast. Depending on their expertise level, some volunteers may help the leading team check data gathered by other volunteers, a peer-to-peer cross-validation process (Deguines et al., 2018; Kosmala et al., 2016). Therefore, with the emergence of 'big data' and the development of machine learning methods and artificial intelligence, volunteer participation has become increasingly necessary to amplify and to refine the exponential progress in treatment and analysis methods (Ceccaroni et al., 2019). A successful example is the development of the 'Leafsnap' or 'Pl@ntNet' mobile app that identifies tree species from pictures of their leaves, fruits, flowers or barks (Joly et al., 2016; Kumar et al., 2012).

2.2.1. Topic. It is worth noting that big data from CS project raise some ethical questions such as the intellectual property of the data and the level of acknowledgement for the volunteers (Vohland et al., 2019): some authors propose to include volunteers in the authorship at least under a collective identity (Vayena & Tasioulas, 2015; Ward-Fear et al., 2020). These challenges would deserve a review per se, which is not the scope of this one.

2.3. Make a CS community

Online project platforms facilitate discussion between experts and volunteers to share results and questions about the project (Gouveia et al., 2004). Scientists can present preliminary or intermediate results based on the first collected data to inform participants about project progress. Concomitantly, it allows interactions through forums, chats or even video meetings, where volunteers are free to ask questions. These discussions bring scientists closer to the public, and vice versa, and make the relationships less hierarchical. This point is very important regardless of the scientific background of the participants: novices can feel more confident and progress rapidly, which is highly fulfilling (Deguines et al., 2018), whereas the more knowledgeable volunteers may be part of the discussion in the data analysis. Engaging volunteers in data analysis is, however, time-consuming if the scientific team aims to achieve volunteer empowerment. The task may be ensured by a 'facilitator', that is, someone dedicated to training or educating volunteers on a CS project (Lorke et al., 2019), but we propose to enlarge this role to align classes/teachers expectations and scientific objectives of the research team. The facilitator should not be substituted for the interactions between volunteers and scientists but instead be a hyphen between both, facilitating their interactions.

2.4. CS in the classrooms

An increasing number of CS projects involve schools (Kermish-Allen et al., 2019; Nistor et al., 2019; Van Haeften et al., 2021), even if they are often not specifically designed for students (Bopardikar et al., 2021; Williams et al., 2021). The scientific team can take advantage of the time dedicated by the class to the project to train students and improve data quality (Castagneyrol et al., 2020). This does not avoid the requirement for another check after data collection, but it also creates a time for discussion with pupils and teachers about scientific methods and epistemology. This aspect of CS is at least as important as the larger time and spatial scale of data collection because it allows students, and people in general, to be more aware of the world's complexity (Morin, 2007). From a quantitative plant sciences perspective, it is important to clearly explain the benefits of acquiring a large amount of data for building a robust answer to the initial questions, stressing the importance of the variability at different levels of organisation.

Although developing CS with schools appears to be relevant, scientists need to factor in educational constraints that are often incompatible with the protocols. Indeed, teachers do not have an infinite amount of time to allocate to the project, which can have consequences on data validity or decrease the project's relevance for students and teachers, despite the educational benefits of CS initiatives (Esch et al., 2020). Tools and protocols may have been thought to be easily used by non-scientific experts, and the classroom constraints may limit the involvement in a CS project.

Moreover, cost, logistical tensions or effort to motivate students with 'fun' activities for instance are some knock-down barriers that still remain in addition to schedule constrains (Roche et al., 2020). Therefore, a 'facilitator' may allow, at the genesis of the project, to build a project that meets the requirements of all participants.

3. CS projects: Reciprocal benefits for citizens and academia

3.1. Main benefits for the scientific community

From the scientist point of view, CS projects represent an unprecedented opportunity to rely on an important number of volunteers collecting data (Fig. 2, orange arrow). The 'many-eyes hypothesis' has been developed to describe the efficiency of CS in generating, scrutinising and analysing data across vast spatiotemporal scales and multiple taxa (Dickinson et al., 2012; Earp & Liconti, 2020; Thomas et al., 2017). In the case of CS, the hypothesis demonstrates that a larger group of people increases the chance of detecting a species/phenomenon and can survey a vaster region. For instance, 'The conker tree science' project studied the effect of pest controllers on leaf-mining moths damaging leaf conker trees (http://www.conkertreescience.org.uk/). Researchers asked volunteers to collect infected leaves and count insects that had hatched out. The protocol was very simple, and 3500 citizens, covering all Great Britain, sent their results to the researchers (Pocock & Evans, 2014). The 'Oak Bodyguard Citizen Science Project' has also successfully estimated caterpillar herbivory on *Quercus robur* in Europe, thanks to an easy protocol, freely available, proposed to different European classes (Castagneyrol, 2019). These two examples highlight the larger area covered by participants: 'The conker tree science' project provides results at a national scale when the 'Oak Bodyguard Citizen Science Project', on a European scale, has increased the number of sampling points in different countries. It now includes new countries such as Latvia and Lithuania where no scientist works on the project (Castagneyrol et al., 2020). The large-scale response of Conker and Oak trees was obtained, thanks to local volunteers, which would have been unreachable with professional scientists only.

The development of CS is also an efficient way to widely communicate the results from a research topic. Indeed, CS projects imply generally some side activities, which are not directly linked to the scientific experiment itself. These activities take place in the context of the scientific project, and it is then easier to develop outreach activities with the volunteers as they benefit of the same background. However, to be the most effective, it would judicious to plan it when project leaders build the project (Lakeman-Fraser et al., 2016).

An increasing number of funders (e.g., the European Union) ask to make the results of projects they supported publicly available. We strongly support the spread of scientific result, whatever the means (Poulet et al., 2021), but we recognise the holistic benefit from participating to a scientific project while learning about the scientific topic and research functioning. The implementation of CS in the research project makes this dissemination step easier, combining scientific knowledge production and outreach activities.

3.2. Important benefits for volunteers

The direct benefits for volunteers participating in CS projects consist first of increasing their own knowledge and/or scientific and technical skills. Practising science makes the learning process more efficient because volunteers face the same constraints as scientists, which makes more sense to the volunteers (Fig. 2, blue arrow, Bonney et al., 2016; Freitag, 2016; Kermish-Allen et al., 2019; Shirk et al., 2012). This praxeological approach may be seen as a much more stimulating method than passively listening to a lecture or conference (Barragan-Jason et al., 2021; Smith et al., 2021). The relationship between professional researchers and the public is often limited to conferences and questions to the researcher who 'knows' and the audience who 'learns'. This method of knowledge transmission is important but should be completed by peer exchanges, that is, between non-professionals, when a volunteer belonging to the project community becomes the link between the project and the audience. The discussion among non-professionals allows the removal of the potential distance that the public can feel between themselves and the researcher (Burke et al., 2016; Watermeyer & Montgomery, 2018).

We think that transdisciplinary research programs may be more attractive, as they mix different fields. For example, the Growing Beyond Earth (based in the USA) project enables students to work on a transdisciplinary project where quantitative plant science meets microgravity and space exploration *via* a CS project led by the Fairchild Botanic Garden (Miami, FL) in partnership with NASA (https://fairchildgarden.org/gbe/). The objective is to identify resistant crops for spaceflight, and as a result, astronauts have grown Pak Choi on the ISS after it was identified as suitable by the large amount of data collected by students. The European Space Agency is pursuing the same objective as the Astroplant project, encouraging citizens and classrooms to gather data on plant growth using a DIY desktop greenhouse (https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/AstroPlant_citizen_science_for_growing_plants_in_space).

The Space Chile Grow a Pepper Plant Challenge (https://five.epicollect.net/project/the-spacechilechallenge-cose) is another NASA CS project launched in preparation for an ISS experiment that engages citizens in collecting data on indoor chilli pepper cultivation to tackle some of its inherent challenges. The high valuation of space research in the media makes the task very exciting for volunteers, and it becomes easier for researchers to 'reward' participants with visible communication.

3.3. CS: A ways to link citizens with research projects

This deeper understanding of science would strongly support ecological preservation and restoration (Fig. 2). Ecological restoration and preservation programs have succeeded, thanks to the implication of volunteers in different steps of the project and in the decision-making process (Buldrini et al., 2015; Conrad & Hilchey, 2011; Kobori et al., 2016). Indeed, volunteers involved in CS projects can be seen as vectors of knowledge dissemination by speaking about the project and the results to people around them (Burke et al., 2016). In this way, volunteers become 'advocates of environment conservation', such as in the 'Ansa e Valli del Mincio' protected wetlands where volunteers have monitored invasive species (Buldrini et al., 2015). Similarly, a successful program was designed in Texas to monitor *Arundo donax*. The CS program reported an increase in the giant reed area distribution and can be a scientific resource for ecosystem management (Gallo & Waitt, 2011). In 5 years (2005–2010), volunteers reported 9004 observations, which represent 3416.75 h of work. The large-scale monitoring, during a long period, may be hard to set up and the assistance of volunteers helps make plant monitoring more sustainable in space and time. Another fulfilling aspect of CS

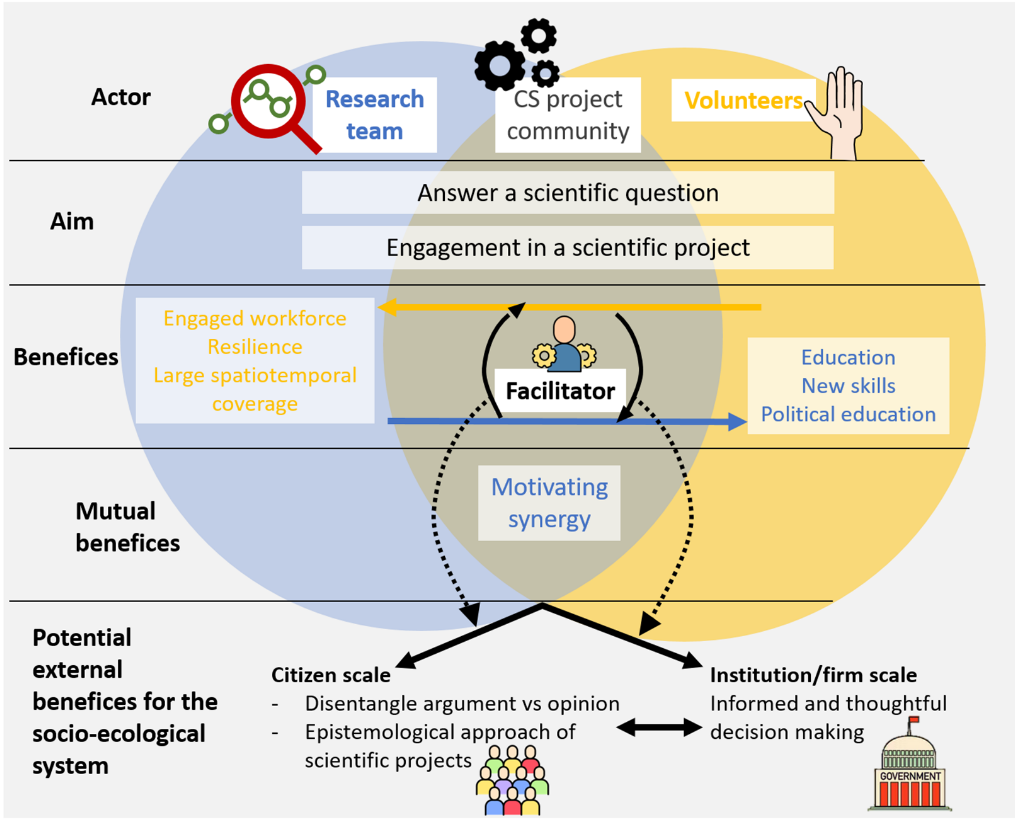

Fig. 2. Conceptual framework of the reciprocal benefits from the CS project to the socio-ecological system. Circles represent participants of a CS project, and black arrows show how the scientific and epistemological benefit spreads beyond the project per se. The two dotted arrows represent the indirect added value of the facilitator to spread the CS results to the socio-ecological system.

projects consists of the more important involvement of volunteers in environmental protection agencies (Owen & Parker, 2018). Even if there are still some challenges with some CS projects regarding the inclusion of results in environmental policies despite the merits of the CS approach (see Section 3 and MacPhail & Colla, 2020), an increasing number of governments recognise the significant role of citizens in nature preservation and rely on CS projects to act and make decisions. Similarly, a recent global scale review has highlighted that involvement of Indigenous peoples and local communities in the management and decision making represents the primary pathway to effective long-term conservation of biodiversity (Dawson et al., 2021). Nascimento et al. (2018) recall that the Scottish government helped some CS projects with training and tools to improve their data collection. This action shows the confidence and value of citizen engagement in nature conservation. Governmental acceptance of CS projects in the formation of policy allows reciprocal benefits not only between volunteers and scientists, but it allows the benefits to spread across society, thanks to the higher citizen involvement in public policies, which is reflected by the increased financial support to CS (Schade et al., 2021).

CS projects would help to reconnect our society to nature (Barragan-Jason et al., 2021; Gaston & Soga, 2020) and increase public awareness of the current status of the environment and the threat that humans represent to ecosystem stability (Cerrano et al., 2017; Schläppy et al., 2017). In line with these authors, we want to show that the objectives of CS go far beyond helping research teams or educating the public about the sciences (Bonney et al., 2014; Vignola et al., 2009): In a global change context and a highly complex world, the involvement of citizens and researchers in a more socio-ecological democracy is critical to facing the dangerous global crisis in which we are currently living (Gardner & Wordley, 2019; Hagedorn et al., 2019; Steffen et al., 2015).

4. Remaining challenges to improve CS

4.1. Data quality

The suspicion about data quality often rises first in CS projects (Kosmala et al., 2016). Data quality is the outcome of several components (Pipino et al., 2002), but data accuracy emphasises most of the criticism, that is, the precision of the data relative to its real value. In other words, is the data reported by a volunteer correct or not? The concern may be legitimate because of the diversity of background, training and involvement of volunteers. However, this concern may also be true for professionals (Castagneyrol et al., 2020; McKinley et al., 2015; McKinley et al., 2017) and should not be an initial bias in the mind of editors and reviewers. Indeed, Kosmala et al. (2016) started their review about CS data quality by citing several projects that led to many publications (Fig. 1), which should make quantitative plant scientists and others more confident about their involvement in CS projects.

As it is not yet a common practice, researchers will need to design CS-dedicated experimental protocols (Burgess et al., 2017; Pocock & Evans, 2014), and sometimes researchers are challenged by short-term funding (Crall et al., 2010; Vasiliades et al., 2021). Therefore, the help of citizen organisations may first link researchers and volunteers by training and supporting volunteers during the process. However, we think that it is of great importance that researchers become involved in the process of sharing science (i.e., training, interacting with volunteers), which is part of their duties. It is not the role of NGOs or associations to remedy the malfunctioning of states or scientific financial institutions, especially in context of social, health, economic and environmental crises (Vohland et al., 2019). What is today a potential 'waste of time' in the mind of some researchers should become part of their daily work and will provide a high return on investment during data analysis. Similarly, the data check should be a necessary task, as is the case when professional scientists collect data (Castagneyrol et al., 2020; Cox et al., 2012). As researchers, we have to consider the great advantage of CS for quantifying variables of interest at a larger scale and then accept that we will have to spend more time cleaning the data and supporting volunteers.

4.2. Volunteer motivation

Cherry trees in Japan have been monitored for more than a thousand years (Kobori et al., 2016). This example highlights the critical aspect of volunteer motivation for the success of these research programs. The resilience of CS projects (i.e., their ability to keep running or restart despite obstacles) is an asset for medium-long-term data requirements (Couvet et al., 2008).

To increase volunteer motivation, we believe that the feeling of being a useful piece of the research program may strengthen the involvement of volunteers in the project and open it to new people, as volunteers devote their free, unpaid time (Conrad & Hilchey, 2011; Lakshminarayanan, 2007). Volunteer engagement increases if at least the subset of the data they collected may participate in answering local challenges (Freitag, 2016). Schools may represent a more reliable way to ensure student involvement, at least for 1 year. The CS project would benefit from dedicated time by the class to the project tasks but also to an educational time on science epistemology with the teacher and the researcher involved in the project (Castagneyrol et al., 2020; Poulet et al., 2021). We acknowledge that the project might be a mandatory part of the curriculum rather than a voluntary one, but we hope that students' contributions to CS projects may open them to new topics and inspire them for future participation.

To involve more volunteers generally in the sciences through CS projects, it is also important to deconsecrate researchers in the eyes of the public. Without the volunteers' contribution, the scientific project would not exist. Therefore, the project not only belongs to the research team but also to the volunteers who sometimes contribute to the easiest but essential and/or tedious tasks. The globalisation of research collaboration can be enhanced by CS and by considering volunteers worldwide. Currently, there is a high CS project concentration in the Northern Hemisphere, especially in Europe and North America (Earp & Liconti, 2020; Thiel et al., 2014). However, to multiply the positive feedback of CS projects, it would be necessary to extend the spatial localisation of these projects.

4.3. Connecting scientists and volunteers

Finally, to make science an efficient citizen tool, researchers must involve volunteers deeper into the project's governance (Conrad & Hilchey, 2011; Heigl et al., 2019). The basic level of CS consists of collecting data, which *per se* has a significant impact in increasing the size of a dataset – which is particularly interesting in quantitative science. However, a transition from projects whereby participants mainly collect data to more collaborative and co-created approaches has started and needs to continue (Bonney et al., 2009; Teleki, 2012), with major socio-ecological benefits such as promoting environmental awareness and literacy and empowering citizens and communities. We acknowledge that it is not an easy task to build such a project (Eleta et al., 2019). Coordinating the group requires a lot of time and energy, a task that could be carried by facilitator. However, there are already some encouraging examples. 'The gardenroots' project worked on the role of soil contamination in edible plants and human health and it is driven by a non-expert group in collaboration with a researcher. The whole group participates in the experimental design, data collection, analysis, and decision-making process (Ramirez-Andreotta et al., 2015). Reis and Glithero (2015) showed that even at school, students participating in a CS project can go further than the scientific question, even raising some ecojustice considerations for the benefit of all. However, examples are rare and this holistic goal of CS deserves more research and discussion among stakeholders. The task is huge to democratise this approach but we hope that the scientists working with CS will mobilise in that sense in the future.

Different classifications exist in the literature (Table 1) to highlight a gradient of volunteers' involvement in the project's tasks. It is out of the scope of this review to clarify the possible overlap among the terms, but all recognised that the more that volunteers participate in the scientific process (from conception to solution application when the goal was to solve a local issue), the greater they are empowered. It has positive consequences on the citizenry because they become aware of how the data are collected and how data are used, they understand where the money comes from and how it is spent, and finally, they can participate in the decision-making process more easily. This can lead to substantial policy changes, thanks to an awareness of involvement in scientific and societal issues (Hagedorn et al., 2019). Therefore, a specific effort from research teams is needed to allow democratic shared governance (Watermeyer & Montgomery, 2018) regardless of the degree of involvement of volunteers.

To conclude, the strength and weakness of CS projects are the participant diversity in terms of scientific level, expectations and motivation. To avoid disappointment, we agree with Lorke et al. (2019), who encourage the participation of a facilitator early in the co-construction of the project.

4.4. We need more than guidelines for citizen science

Working on these different points can result in good practice guidelines and toolkits for the future of CS (Silvertown, 2009). Bonney et al. (2009) and Tweddle et al. (2012) offered a roadbook to efficiently start a biodiversity CS projects with some plant science precisions. The main points can be summarised as: (1) choose a scientific question; (2) form a scientist/educator/technologist/evaluator team; (3) develop, test and refine protocols, data forms and educational support materials; (4) recruit participants; (5) train participants; (6) accept, edit and display data; (7) analyse and interpret data; (8) disseminate results and (9) measure outcomes (Castagneyrol, 2019; Hill et al., 2012; Teacher et al., 2013). We advise readers to refer to the chapter written by García et al. (2021) for a more detailed review of the existing guidelines in the book directed by Vohland et al. (2021). Online platform sharing protocol is also a way to give or to check experimental instructions before engaging in a project as Castagneyrol (2019) did for the 'Oak bodyguard Citizen Science project' on https://www.protocols.io. However, as this review aims to demonstrate, a CS project is not as simple as a 'recipe' because each group of volunteers has its own features.

Table 1. Summary of citizen science governance types

CS program	Volunteer implication	References
Consultative and functional	- Data collection	
	- Protocol application	Conrad & Hilchey (2011)
	- Project construction	Lawrence (2006)
Collaborative and transformative	- Data analysis	Earp & Liconti (2020)
	- Results communication	

The potential of CS projects for spreading science and the scientific method to the socio-ecosystem may be enhanced if the objectives and limits of each group of participants are taken into account (Freitag & Pfeffer, 2013). A third party may ensure the match between each stakeholder: For global projects, finding a local interest for volunteers is important to reinforce their engagement and empower them scientifically and democratically (Esch et al., 2020; Golumbic et al., 2017; Lorke et al., 2019). In a classroom, teachers are limited in adapting the curriculum; therefore, the facilitator may help scientific project leaders adapt the protocol to academic constraints. More generally, the interest and skills of volunteers may evolve during the project, leading to changes in their motivations (Rotman et al., 2012). Anticipating the dynamics of volunteer involvement in the project design can enhance the expectations of all participants by stimulating volunteers. As suggested by Zoellick et al. (2012), the university may play this role of facilitator with students or a specialist of scientific mediation could also assume the role. Local organisations interested in a project may also make the link between scientific teams and the volunteers such as naturalist or environmentalist associations, or at a bigger scale, naturalist learned societies or NGOs.

5. Perspectives and conclusion

CS is currently at a crossroads of demonstrated successes, unresolved challenges and unrealised potential. In particular, the potential mutual benefits for researchers, volunteers and society are still undervalued. These mutual benefits occur at different scales: to solve the research question driving the project, the educational aspect towards the volunteers and the dissemination of knowledge through society. Depending on the involvement of the volunteers in the project, the outreach exchanges can be more or less integrative. Finally, the ongoing crises (health, economic, social and environmental) have highlighted the crucial role of science in explaining the world's complexity and overcoming obstacles.

On the other hand, citizens are increasingly solicited in the decision-making process in society, and thus they need to have the strongest background possible to make decisions and change their behaviours (Eymard, 2020; Vignola et al., 2009). Ecology and especially plant ecology have used CS for a long time and are precursors in CS. Applications to identify plants are widely available to the public, and an increasing number of people have participated in global databases, such as those about plant phenology, sometimes for hundreds of years (Amano et al., 2010; Amano et al., 2014; Bopardikar et al., 2021). The long experience of CS projects has allowed to know the strengths and weaknesses of this approach and to propose tools to limit biases (Bird et al., 2014; Bonney et al., 2009; Kosmala et al., 2016). Still related to plants, the space field has also largely included CS projects, with exciting perspectives for space exploration (see the examples mentioned in Section 2.2). Thanks to this experience, it appears that CS requires changing the typical project construction approach by including, ideally, a facilitator, changing the typical way to make a protocol. This may be the strongest upheaval that some researchers have to face, especially in quantitative plant science but also in other disciplines. We hope this review provides exciting examples and a large body of literature to help quantitative plant biologists become more confident in this approach. The benefit may be significant from a scientific production point of view, but it can also have a crucial social role for public opinion of science and CS. Therefore, we encourage researchers and citizens to promote and launch a CS program for the essential benefit at the socio-ecological scale, spreading the benefits of CS to a more global scale (Fig. 2, Devictor et al., 2010; Hano et al., 2020; Lawson et al., 2019).

In our opinion, this may be the main point of CS: Science and knowledge result from a long and rigorous demonstrative process, which gives it a different status from beliefs, ideology or opinion, and this is what researchers should emphasise during their collaboration with volunteers (Poulet et al., 2021). The active participation of people in scientific research facilitates the transmission of this approach to world complexity and the associated processes. It helps people disentangle scientific arguments from other information and opinions during debates and fight against obscurantism (Eleta et al., 2019). Finally, it can help people build stronger critical thinking skills about our socio-ecological issues and influence the decision-making process (Fig. 2, Carolan, 2006; Heathcote et al., 2019; Shanley & López, 2009).

However, one point still deserves more attention: How can we honestly 'reward' volunteers for their contributions? The publication of articles is very rewarding for researchers. It contributes to the progress of their careers and helps to find new funding for projects. However, it is impossible to include all volunteers in the authorship (but see Ward-Fear et al., 2020), and they would not strongly benefit from this acknowledgement. The project we have launched, the outreach research journal DECODER, proposes publishing an outreach version of an article published in international scientific journals in collaboration with one of the authors and articles written by classes and reviewed by an expert (Poulet et al., 2020; Poulet et al., 2021). We acknowledge that this is not strictly a CS project, as it does not produce new scientific knowledge. However, it may be a way to value the work of a class or volunteers by producing and publishing a public-targeted version of their work. A similar initiative was created by Frontiers journal, https://kids.frontiersin.org/. Volunteers can use the whole dataset or only a subsample corresponding to the data they collected, and they can reformulate the question in the context of their environment (Ledley et al., 2011). Publishing results and manuscripts from volunteers and classes in open access give more value to their contribution (Burke et al., 2016). It can be a way to 'reward' them for their work. Then, a comparison with the published version of the research may constitute an interesting tool to address the role of big data in the impact of environmental conditions on the variables, for instance. Another approach would be to have the researcher or institution leading the project gives a certificate to volunteers. It would be interesting to build a standard nomenclature to recognise the work of the volunteers and allow them to use the training they received during the project for a new one, thanks to this standardised system of skills acquisition.

Acknowledgements

We want to thank all the teachers, students and researchers who have trusted us on the DECODER project. They have inspired us to engage in outreach science and to write this review. We also thank Geoffrey Volat for the interesting discussion about the praxeological approach and Pr Olivier Hamant for inviting us to write this review.

Financial support. This research received no specific grant from any funding agency or from commercial or not-for-profit sectors.

Conflict of interest. None.

Authorship contributions. A.R. and A.V. wrote the first draft of the manuscript. A.R. drew Fig. 2, and B.D. and A.R. drew Fig. 1. All authors contributed equally to improving the first version.

Data availability statement. This review does not rely on any data, code or other resources.

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