CITIZEN SCIENCE:
THEORY AND PRACTICE

Citizen Science: Pathways to Impact and why Participant Diversity Matters

RESEARCH PAPER

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ABSTRACT

Citizen science has a problem with engaging diverse participants, with a growing number of studies showing those most marginalised in society, who could benefit most from citizen science activities, are the least likely to participate. The full implications of this lack of diversity for what citizen science can achieve remains unexplored. To do this, we reviewed the literature to create a comprehensive list of 70 proposed benefits, outcomes, and impacts of citizen science. We used this list to construct 9 pathways to impact, showing how short-term project outcomes under the themes of data, participant engagement and collaboration lead to a suite of medium- and long-term outcomes. We then explored how a lack of diversity in citizen science participants can cascade through these pathways, affecting the overall ability of citizen science to achieve its myriad potential impacts and further entrenching disparities in society. We advocate for project leaders to use a pathways to impact approach to explore how who they recruit will affect what their projects can achieve. We also call for greater imagination in exploring, testing, and sharing ways in which barriers to participation can be understood and overcome to open citizen science up to all and to achieve its potential.

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INTRODUCTION

Diversity in citizen science (CS) is the extent to which participants represent the "differences amongst individuals, including demographic differences such as sex, race, ethnicity, sexual orientation, socioeconomic status, ability, languages, and country of origin, among others" (NASEM 2018, p. 18). While many CS projects collect little or no demographic data about their participants (Moczek, Hecker, and Voigt-Heucke 2021), a growing number of studies have shown CS suffers from challenges with diversity in participation globally (NASEM 2018), nationally (Mahmoudi et al. 2022), and locally (Domroese and Johnson 2017). As Lewenstein (2022) puts it, "CS, like other forms of public engagement, involves inequality" (p. 184). Although there are exceptions (e.g., Purcell, Garibay, and Dickinson 2012; Sorensen et al. 2019), the majority of projects engage participants who "represent empowered people" (Lewenstein 2022, p. 187). The CS diversity literature is dominated by studies from the Global North, which show that in this context men are more likely to participate than women (Pateman, Dyke and West 2021), white people are more likely to participate than those from other ethnicities (Allf et al. 2022), and participants are likely to have completed at least one educational degree (Vasiliades et al. 2021) and be affluent (Blake, Rhanor, and Pajic 2020). Less is known about other aspects of diversity such as sexual orientation and ability; and the demographics of participants in the Global South are poorly understood, although there is some evidence to suggest there are also challenges with recruiting from marginalised groups in these contexts (Pateman, Tuhkanen, and Cinderby 2021).

The consequences of a lack of diversity among CS participants are only just beginning to be revealed. Studies have recently shown, for example, how who participates affects the types of place or people represented in datasets (e.g., Baker et al. 2019; Blake, Rhanor and Pajic 2020). How inequalities in participation limit the perspectives brought into the scientific process (Lewenstein 2022; Sauermann et al. 2020) and who gains benefits from participating, such as new skills, knowledge about their local environment, and career opportunities (Pandya 2012), have also been discussed. However, a full understanding of the consequences of a lack of diversity in CS participants is missing. Therefore, in this paper, we seek to extend our understanding by identifying the pathways through which impacts can arise from CS and explore how the consequences of who is and who is not recruited and retained in projects can cascade through short- and medium-term outcomes to ultimately affect potential long-term achievements. First, however, we give an overview of the literature relating to impact planning in the context of CS.

IMPACT PLANNING AND CITIZEN SCIENCE

There is growing recognition of the need to better understand, plan for, and measure the impacts of CS (Wehn et al. 2021) in order to facilitate their realisation, and to document successes and challenges to develop best practices. Consequently, frameworks that categorise the types of impact that can arise from CS have been produced. Kieslinger et al. (2018), for example, identify three dimensions: scientific, participant, and socioecological and economic; Wehn et al. (2021) identify five "impact domains": society, economy, environment, science and technology, and governance (p. 1683); and von Gönner et al. (2023) identify CS impact through scientific practices, participant learning and empowerment, and socio-political processes. In turn, resources have been developed to help project leaders plan, foster, and evaluate impact within CS, such as the Measuring Impact of Citizen Science (MICS) tool (MICS n.d.) and the Open Framework for Evaluation in Citizen Science (Kieslinger et al. 2018).

Part of impact planning can entail mapping how desired impacts of CS projects will arise from project activities via intermediate outcomes, which allows impact to be carefully planned for, as well as provides a plan against which project evaluation can take place (Wehn et al. 2021). A range of approaches can be used. Logic models, for example, map the linkages between project resources (or inputs), activities, outputs, outcomes, and impacts (Schaefer et al. 2021), and have been used to map impacts from biodiversity-related CS surveys (Phillips, Bonney, and Shirk 2012). Others use a theory of change approach, for example to explore conservation outcomes from CS (Ballard, Phillips, and Robinson 2018). This requires detailing actors involved in the system, assumptions underpinning any action, and provides a structure for evaluation (Center for Theory of Change n.d.-a). Creating a pathway through outcomes to impact (sometimes called an Outcome Framework [Center for Theory of Change n.d.-b]) or a pathway of change (Nitsche n.d.) is an important step in the process of creating a theory of change. Van Noordwijk et al. (2021), for example, use a pathways to impact approach to devise six pathways through which positive environmental change can occur from CS.

In this paper, we build on previous CS impact-pathway mapping studies, which have looked at particular topics (e.g., the environment) or categories of impact (e.g., education) by constructing pathways to impact across all topic and impact areas. We do this by reviewing the CS literature to identify the proposed benefits, outcomes, and impacts of CS, and by using these to describe pathways through which impacts can arise. We then use these pathways to describe how biases in participation could cascade through the pathways, limiting the impact CS can ultimately achieve. Our aims are to encourage CS practitioners to consider how who is participating in their project will have consequences for the impacts they are hoping to achieve, and to encourage users of CS datasets and results (including researchers and decision-makers) to consider how who participated in a project might influence the conclusions they are able to draw from these datasets. Our ultimate goal is for CS projects to be designed in a way that they are open to participants who are representative of the societies in which they are based.

METHODS

LITERATURE REVIEW

We reviewed the academic literature to gain a comprehensive list of benefits, outcomes, and impacts of CS proposed by CS practitioners, researchers, and data users (stages 1 and 2 in Figure 1). Owing to time constraints, we were unable to implement a full systematic review, so we adapted and shortened this methodology to carry out a rapid review of the literature. Our first step was to search Web of Knowledge using the terms "citizen science" AND (benefit* OR outcome* OR impact*) on 21st April 2022. This gave 2,179 results (after four duplicates were removed), which were imported into Rayyan and sorted alphabetically. The authors read abstracts independently, each starting at a different end of the list, and coded them according to categories of benefits, outcomes, or impacts of CS mentioned in the abstract. Each time a new code emerged, it was added to a list shared between the authors along with a brief definition. Each author began by reading and coding 25 abstracts that were then reviewed by the other author. Any disagreements were discussed to reach consensus and to develop a shared understanding of the code. After this, the authors coded independently, adding and referring to the shared list of codes, which was regularly discussed to ensure consistency. Categories and descriptions along with an example article and quote from its abstract are shown in Supplemental File 1: Appendix A. Suggested or potential benefits, outcomes, and impacts were included, as were those for which clear evidence was provided as we were interested in the full range of potential benefits of CS. The authors read abstracts until both had read 20 without adding any new categories, resulting in information being extracted from 337 sources (see Supplemental File 1: Appendix B for the full list of sources). While this generated a long list of outcomes that reflect those identified in other impact frameworks, a potential limitation of this approach is that outcomes not listed in abstracts, and those that are less common, may have been missed.

PATHWAYS TO IMPACT

We used the categories derived from the literature to construct pathways to impact for CS (stage 3 in Figure 1). We started by identifying outcomes that could be

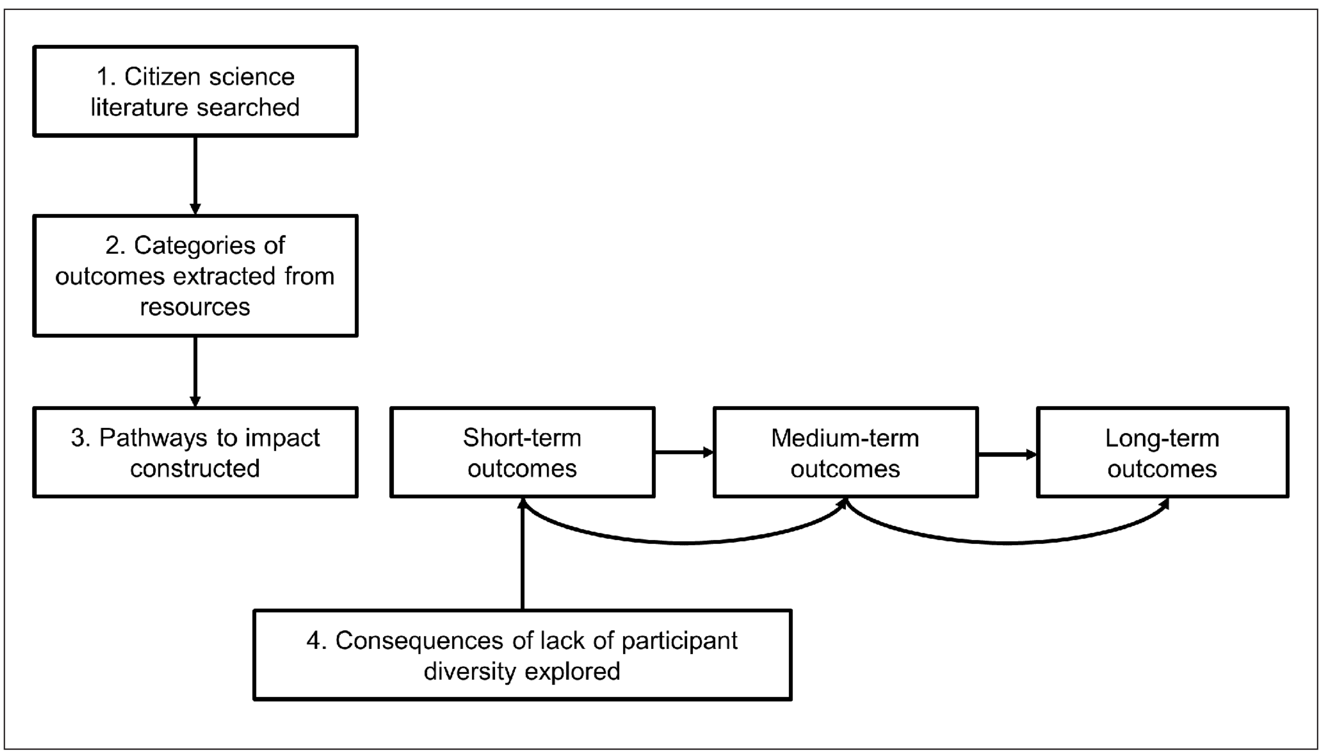

Figure 1 Overview of the study methodology, showing the four different stages.

considered short term (i.e., emerging within or shortly after the lifetime of a project). These were clustered into related outcomes, which gave us nine starting points for pathways. We then used the remaining terms to map logical medium- and long-term outcomes arising from these starting points. For brevity and clarity in Figures 2–4, some of our original categories were combined into single-category terms, as detailed in Supplemental File 1: Appendix A. For example, "time saving" and "money saving" became "less time and money used." In some pathways, additional outcomes not identified in the literature were added for the purposes of making the flow through the pathway clearer, for example, "Datasets accessed and used by others" was added to pathway 3 (additions are also detailed in Supplemental File 1: Appendix A). These logical pathways were constructed based on the authors' experiences with designing, running, and evaluating CS. Often when developing a Theory of Change, pathways are refined in a workshop setting with different people drawing connections and adjusting outcomes (Center for Theory of Change n.d.-a). However, this was outside of the scope of this paper and so instead we refined the pathways using the descriptions of outcomes contained within the abstracts of papers read in the literature review.

CONSEQUENCES OF BIASES IN PARTICIPATION

For each of these pathways, we used the linkages we identified from short- to medium- through to long-term outcomes to trace how a lack of diversity in who is participating in a project could cascade through these pathways to affect their ultimate impact (stage 4 in Figure 1). We describe these possible consequences, drawing on our experiences and understanding of CS, and we illustrate them with examples from the literature where available.

RESULTS

Our literature searches revealed 70 realized and potential benefits, outcomes, and impacts from CS, from which we constructed nine pathways to impact (see Supplemental File 1: Appendix A for the categories and example papers from which they were derived). These pathways clustered into three themes: data, participant engagement, and collaboration. These pathways are described separately below, but it should be noted there are interlinkages between them (as shown by the highlighted outcomes in Figures 2–4, which indicate where outcomes are present across multiple pathways), and many projects aim to achieve outcomes that could fall into multiple pathways. In addition, the timescales through which impact occurs on these pathways can differ substantially; for example, a pathway to changing decisions about how an individual site is managed for nature conservation may be much quicker than pathways to changing urban planning policy, because of the complexity of actors involved. Similarly impacts can also occur at different spatial scales, for example, from an individual person or place, through to national or even international scales (Wehn et al. 2021).

DATA PATHWAYS

Three data pathways are focused on outcomes resulting from the data generated by CS projects (Figure 2): more data (pathway 1), richer data (pathway 2), and open data (pathway 3).

Pathway 1: more data

Many short-term outcomes of CS projects cluster under the concept of generating more data than would be possible if scientists were working alone, saving time and money in doing so. Engaging more people in data collection can result in data being collected over wider geographic areas, at finer spatial resolutions and from a greater diversity of places. Data can also be generated at finer temporal resolutions, over longer time periods or more rapidly, for example, in response to a disaster or rare event. CS can also generate data from places otherwise inaccessible to scientists, for example, because they are on private land or because of security concerns. CS can also be used to produce datasets that include information from and about marginalised and understudied people (and their circumstances or environments), which are often excluded from traditional research approaches. Thus, CS can be thought of as producing more complete and more representative datasets.

Medium-term outcomes resulting from this include the generation of new scientific knowledge. In addition, the spatial and temporal attributes of these datasets mean they can also be used for a range of different applications. Rapid production of cross-sectional datasets can be important for making baseline or snapshot assessments to understand an issue at a particular point in time, whereas those with a long temporal extent are important for monitoring trends over many years, including for environmental indicator monitoring and tracking progress towards targets. Datasets generated over long time periods and at high temporal resolution are also useful for assessing the impacts of social or natural events or the consequences of interventions, such as conservation management strategies. Finally, data collected at high spatial and temporal resolutions and from inaccessible areas are valuable for surveillance, for example, of invasive species.

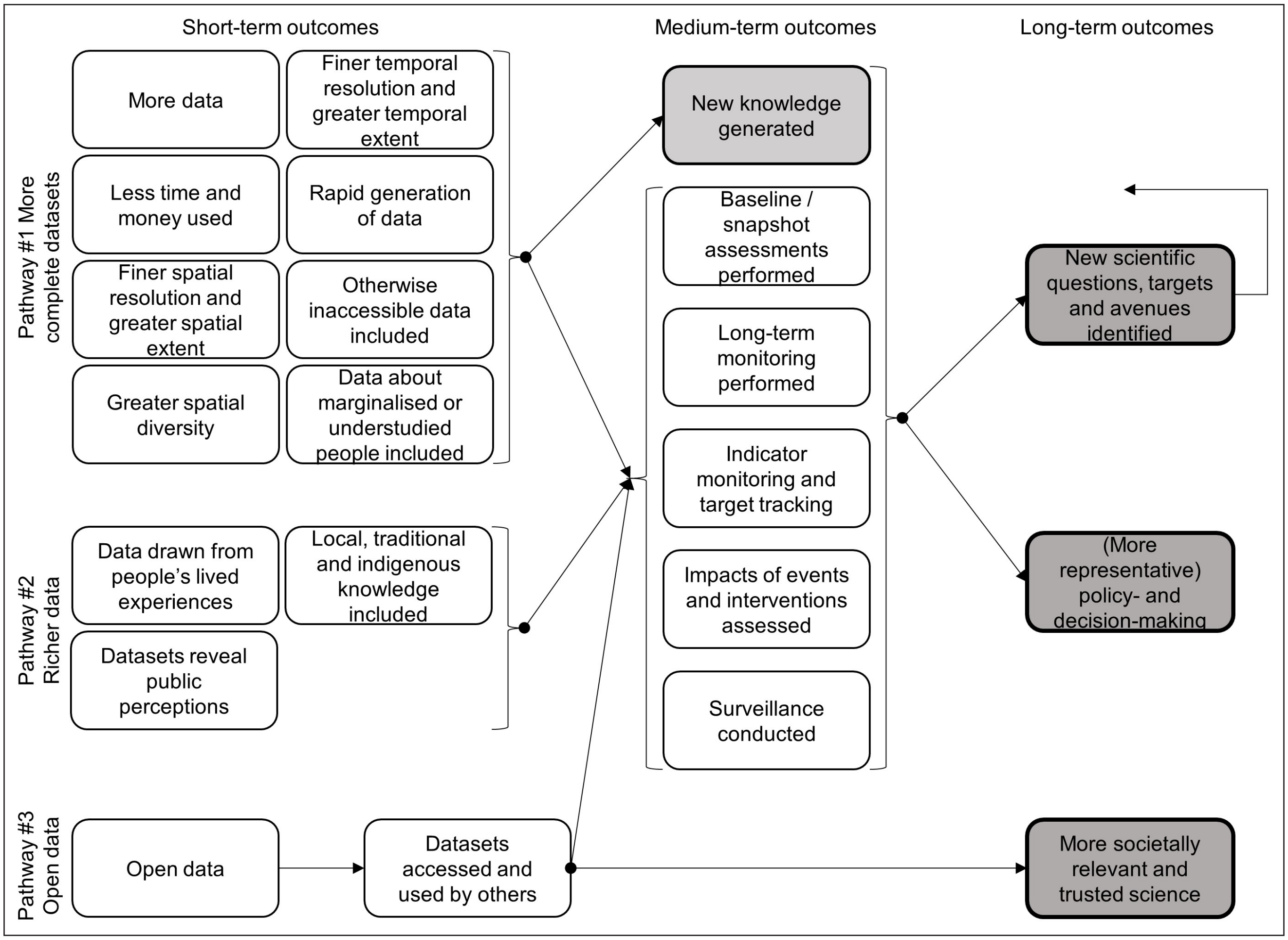

Figure 2 Data pathways. Category appears in two pathway themes (*bold outline and light shading*). Category appears in three pathway themes (*heavy bold outline and heavy shading*).

In the long term, the knowledge generated from these activities can lead to the identification of new scientific questions, avenues, or targets, in turn feeding back into new data collection initiatives. This knowledge can also be used to inform new policy- and decision-making at various scales, from the management of an individual site to urban planning to national or international policies.

Implications of lack of diversity for pathway 1

Consequences of a lack of participant diversity are numerous for this pathway. Firstly, if some groups do not participate in projects, this reduces the overall pool of potential participants, possibly leading to lower participation rates and hence less data being generated than might otherwise be possible. This, in turn, reduces the time and money savings that can result from using CS approaches, and ultimately projects may be less impactful (van Noordwijk et al. 2021).

Second, biases in participation could have consequences for the spatial and temporal completeness of datasets, as has been shown for bird distributions when participants are largely from middle-income areas (Tulloch and Szabo 2012). Furthermore, should biases in the location of participants be correlated with variation in social or environmental conditions, datasets could be misleading. McLafferty, Schneider, and Abelt (2020) show how reports of bed bug infestation in New York City (USA) had strong socioeconomic and geographic biases, which obscured the reality of beg bugs being in predominately high-poverty locations. This has consequences for the ability of datasets to reliably answer scientific questions and monitor issues.

In the longer-term, this could have consequences for the effectiveness of CS data to inform decision-making. Blake, Rhanor, and Pajic (2020) found areas of high environmental justice concern were underrepresented in RiverWatch surveys in Illinois (USA) as participants (who select their own sites and pay a fee for taking part) were disproportionately white, highly educated, and affluent. RiverWatch data are used by landowners, local and regional governments, scientists, and natural resource managers, so the project could contribute to a feedback loop (Blake, Rhanor, and

Pajic 2020 p. 5) in which some communities continue to experience disinvestment and degradation at the expense of areas surveyed by the empowered participants.

Pathway 2: richer data

CS can also generate richer datasets than would be achieved by scientists, who are external to a place or topic of interest, working alone. CS, for example, can draw on the lived experiences of participants as projects can be designed not only to collect data to document an issue but also to understand people's experiences or perceptions of that issue. In addition, CS approaches can produce datasets based on or generated by traditional, local, and indigenous knowledge,[1] drawing on the deep knowledge and insights people have about their local environments and issues that directly affect them and their livelihoods.

As with pathway 1, in the medium term, these richer datasets can produce new scientific knowledge as well as be used for monitoring, surveillance, and impact assessment purposes. For example, these datasets can be used to track how people's responses to or perceptions of particular issues change over time or in response to events or interventions. Datasets that draw on local, traditional, or indigenous knowledge may be particularly useful for monitoring and surveillance purposes as close connection with place can help to detect and document subtle or unanticipated changes.

In the long term, these rich datasets may be particularly useful for informing policy- and decision-making and action, including action by communities involved in collecting and interpreting data. Interventions that consider in their design the knowledge, experiences, and perceptions of those affected by an issue are more likely to be successful in addressing that issue.

Implications of lack of diversity for pathway 2

As in pathway 1, failure to recruit diverse participants could lead to biases or gaps in datasets, in this case in the range of experiences and perspectives represented, which will, in turn, be absent from research and monitoring carried out using these datasets. As such, decisions made and actions taken may not meet the needs of underrepresented groups, potentially leading to limited success and uptake of interventions and further marginalisation of these groups. Pateman et al. (2021), for example, report the case of Transparent Chennai, a digital platform with the aim of crowdsourcing problems experienced by residents to inform urban planning. The tool was intended to be used in particular by marginalised, poor communities but was instead used by the middle classes to inform decision-making, which further marginalised and excluded the communities it was seeking to empower.

Although CS projects that aim to generate datasets from local, traditional, or indigenous knowledge often involve professional scientists (and community and nongovernmental organisations) working closely with communities (Danielsen et al. 2017), they can still struggle to recruit diverse participants (e.g., Benyei et al. 2021). Furthermore, even where these types of knowledge are collected, significant challenges remain with bringing them together with scientific knowledge, and their acceptance in decision-making (Benyei et al. 2021; Danielsen et al. 2017).

Pathway 3: open data

CS datasets are more likely to be open than non-CS datasets (Wagenknecht et al. 2021), meaning they can be accessed, used by, and shared by anyone. Not all CS datasets are open, and in some cases this would be undesirable because of safety or privacy concerns, but when they are open, they can be used by other researchers or decision-makers, on their own or in combination with other datasets, to contribute to the medium- and long-term outcomes described under pathways 1 and 2. Open datasets (and publications) can also, in the long term, democratise science as they can be viewed by and interrogated by anyone, potentially increasing accountability, transparency, and trust, as well as widening involvement in the scientific and knowledge-creation processes (Suter, Barrett, and Welden 2023).

Implications of lack of diversity for pathway 3

While open data facilitates the wider use of data and transfer of knowledge to wider audiences (Wagenknecht et al. 2021), if datasets are problematic due to a lack of diversity in participants (as described under pathways 1 and 2), this could lead to a spread of unrepresentative data and further reinforcement of existing marginalisations. In addition, while data may be open to all, this does not mean all in society have the digital competencies to access and use open datasets and their metadata (Gurstein 2011). Furthermore, open data raises the possibility of unintended and negative consequences of making sensitive information publicly available, including data being used to further marginalise vulnerable communities (Weber and Locke 2022). Thus, even if CS has achieved diverse participation, vulnerable communities may suffer, leading to a reluctance to participate again and to reinforcement of the negative consequences of a lack of diversity in CS.

PARTICIPANT ENGAGEMENT PATHWAYS

These four pathways arise from short-term outcomes for participants: gains in knowledge and skills (pathway 4), science capital (pathway 5), empowerment (pathway 6), and connection (pathway 7) (Figure 3).

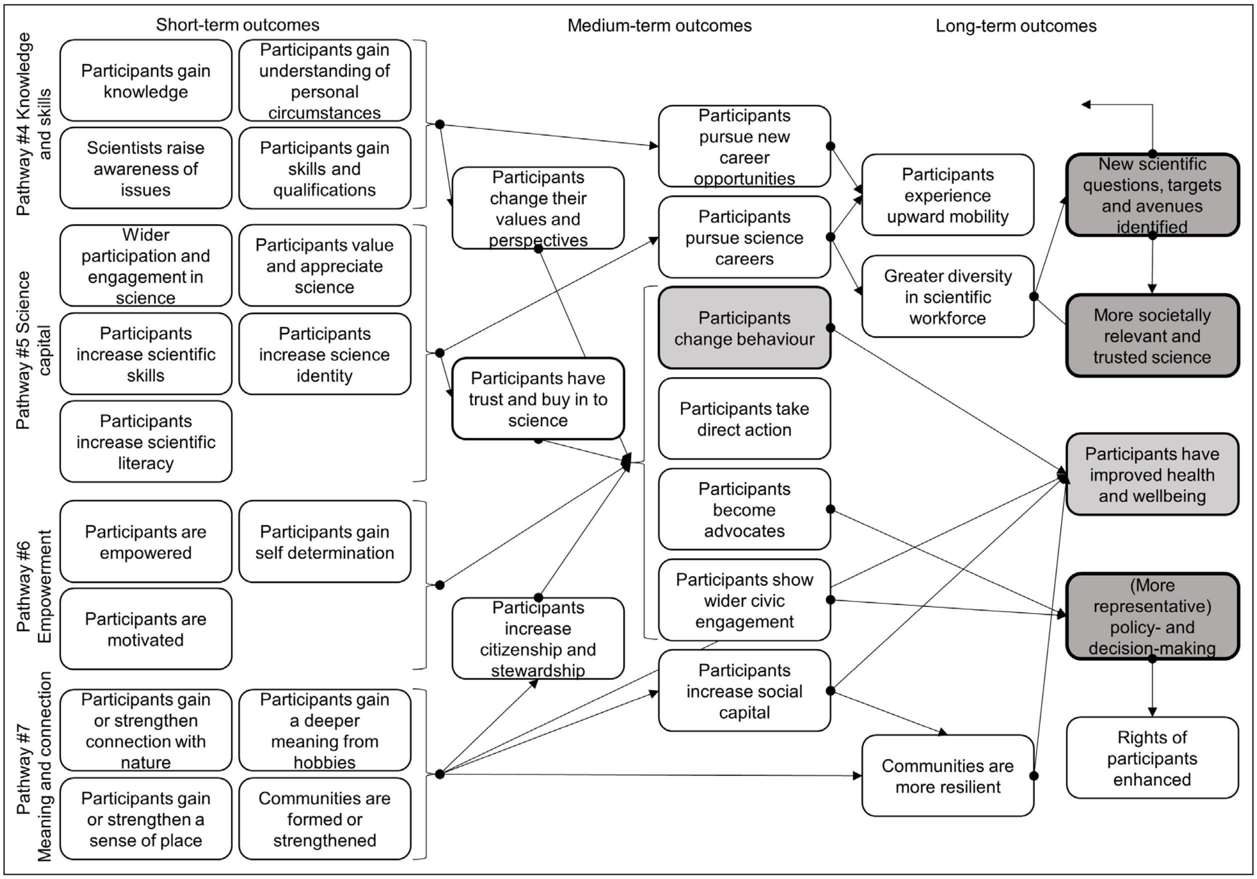

Figure 3 Participant engagement pathways. Category appears in two pathway themes (*bold outline and light shading*). Category appears in three pathway themes (*heavy bold outline and heavy shading*).

Pathway 4: knowledge and skills

In the short-term, participants can gain knowledge, raised awareness (e.g., of environmental or societal challenges), and/or understand their personal circumstances better (e.g., their exposure to particular pollutants). Participants can also gain skills, including technical, communication, team work, and leadership skills. Where CS forms part of a formal education programme, participation can also contribute to formal qualifications.

These outcomes can lead, in the medium term, to participants having the interest and/or tools needed to pursue a career path that might not otherwise have been possible, potentially leading in the long term to upward mobility (where people achieve a higher socioeconomic status than earlier in life[2]). Gains in knowledge, including about one's own circumstances, may also lead to changes in behaviour (in some cases as a result of changes in values and perspectives), which could have benefits for participants' health and wellbeing and for society and the environment more widely.

Implications of lack of diversity for pathway 4

People from groups underrepresented in CS miss the opportunity to gain knowledge and skills through participation. Furthermore, CS participants tend to be already well educated (Martin 2017; Vasiliades et al. 2021) and more affluent (Blake, Rhanor, and Pajic 2020); so those with potentially the most to gain in terms of upward mobility appear to be the least likely to be participating.

Where CS projects seek to change behaviour relating to, for example, health or environmental issues, the omission of particular groups will limit the wider social or environmental benefits that could arise from the project.

Furthermore, for projects in which participants can learn about their own circumstances to inform their behaviour and decision-making, ideally everyone affected by an issue should have access to this information in order to make informed decisions, but this is not always the case. Rappold et al. (2019), for example, report on Smoke Sense, a CS project designed to inform participants about health risks associated with wildfire air pollution so that they can take health protective measures. Those that participated were younger and more educated. and a higher proportion were white and female than the population of the surrounding area. Thus, those from underrepresented groups missed out on the opportunity to learn about their personal risk and how to act to protect their health.

Pathway 5: science capital

Scientists often aim to use CS to widen participation and engagement in science. Participants can gain knowledge and experiences that build their science capital (Edwards et al. 2018), defined as an individual's science-related knowledge, skills, and experiences accumulated over their lifetime (Archer et al. 2015). In the short term, participants can build scientific skills, including practical skills, and scientific literacy (i.e., an individual's understanding of scientific concepts and their ability to apply this understanding to new situations, for example, to think critically and make informed decisions). It can also change people's values and attitudes towards science, including the extent to which they appreciate science and see it as an important part of their lives. Finally, it can build participants' science identity, that is, the extent to which they feel they are a scientist.

These outcomes could lead in the medium term to participants having greater trust in and buy-in to science in general, including its findings and recommendations, which could in turn lead to behaviour change and its resultant outcomes described in the previous pathway. In addition, these outcomes could, in the medium term, give people the skills and interest to pursue a career in science. This could lead in the long term to upward mobility for participants and to an increase in the diversity of people represented in the scientific workforce and a widening of the perspectives and priorities present amongst professional scientists. In turn, this could lead to the identification of new scientific questions, targets, and avenues, and more societally relevant science, with greater trust and buy-in from the wider population.

Implications of lack of diversity for pathway 5

A lack of diversity in CS could limit the potential of CS to increase science capital amongst non-professional scientists, and, in turn, its outcomes, such as public acceptance of science and resulting behavioural changes, which might benefit the environment and society. Edwards et al. (2018) describe the case of UK ornithological CS projects in which participants who did not hold an educational degree reported learning outcomes that could contribute to scientific capital, whereas those who held a degree did not. Those with degrees made up 67% of the participants in the study compared with 33.8% of the wider population.[3] Thus, again, those with the most to gain (this time in terms of gaining scientific capital) were less likely to be participating.

In addition, the scientific workforce exhibits many of the same biases as CS (Charleston et al. 2014) and many CS participants already work in science-related fields (Allf et al. 2022). As such, the potential for CS to be a way to diversify the scientific workforce is currently limited, as are the resultant benefits of this for widening the perspectives and priorities present in science.

Pathway 6: empowerment

CS participants can be empowered, motivated, and gain self-determination through their participation in projects. In combination with knowledge and skills gained (pathways 4 and 5), this can lead in the medium term to participants changing their behaviour, taking direct action to tackle an issue or advocating for their rights with decision-makers or service providers. Participants may additionally be motivated and empowered to become more civically and politically active and engaged beyond the project. These outcomes can lead, in the long term, to policy- and decision-making that better reflects the needs and values of society as a whole, potentially enhancing the (environmental) human rights of participants, and wider society.

Implications of lack of diversity for pathway 6

Biases in participation mean empowerment and the potential outcomes of this for influencing action or decision-making are also limited to certain sectors of society. These outcomes have the potential to improve people's local environments and their health, but if these are achieved only for certain demographic groups, this could further entrench disparities in society. In particular, marginalised groups are often the most affected by environmental pollution or degradation (Walker et al. 2005), but unless specifically targeted, such as in Bucket Brigade water monitoring in the United States (Ottinger 2010), these are often the groups least well represented in CS projects. Failure to target these groups could lead to them experiencing further disadvantage and disempowerment, and this disparity could extend beyond the reach of projects if participation encourages people to become more civically and politically active in general.

Pathway 7: meaning and connection

CS also provides opportunities for participants to gain or strengthen connection with nature, with a place, with a hobby, or with other individuals or communities. These connections can lead directly to wellbeing benefits for participants, as well as an enhanced sense of stewardship and citizenship that could lead to behaviour changes, campaigning, and direct action, either at a particular place, with a particular community, or more broadly, with long-term outcomes as covered under pathways 4–6. Building and strengthening connections between individuals can also increase the resilience of communities to future shocks and challenges, as social cohesion plays an important role in resilience (Aldrich and Meyer 2015).

Implications of lack of diversity for pathway 7

People from marginalised groups often have poorer physical and mental health (Cheraghi-Sohi et al. 2020) and are less connected with nature (Waite et al. 2021) than those from non-marginalised groups. Therefore, those who potentially have the most to gain in terms of the health and wellbeing benefits that can arise from connecting through CS may be the least likely to be engaged. In addition, these groups may also be excluded from the environmental and societal benefits that could arise from action or civic participation that results from this increased connection. Finally, CS has been shown to build community resilience through building collective knowledge of issues, increases in social capital, trust, and sense of community (e.g., Doyle et al. 2020). Communities not socially connected and so less resilient are likely to be disadvantaged compared with those that are more connected via means that include CS participation (Chandra et al. 2011).

COLLABORATION PATHWAYS

The final two pathways are those that are driven from collaborations that can take place within CS projects, either between scientists and citizens (pathway 8) or more widely with other stakeholders such as policy- and decision-makers (pathway 9) (Figure 4).

Pathway 8: science-public relations

CS projects often aim to foster communication and collaboration between scientists and the public. In the short term, by working together and bringing their own perspectives and expertise, these groups can co-produce results not possible if either were working alone. In the medium term, this can lead to the generation of scientific knowledge that would not otherwise be possible, feeding into the long-term outcomes of new avenues of scientific enquiry and informing policy- and decision-making described under the data pathways above.

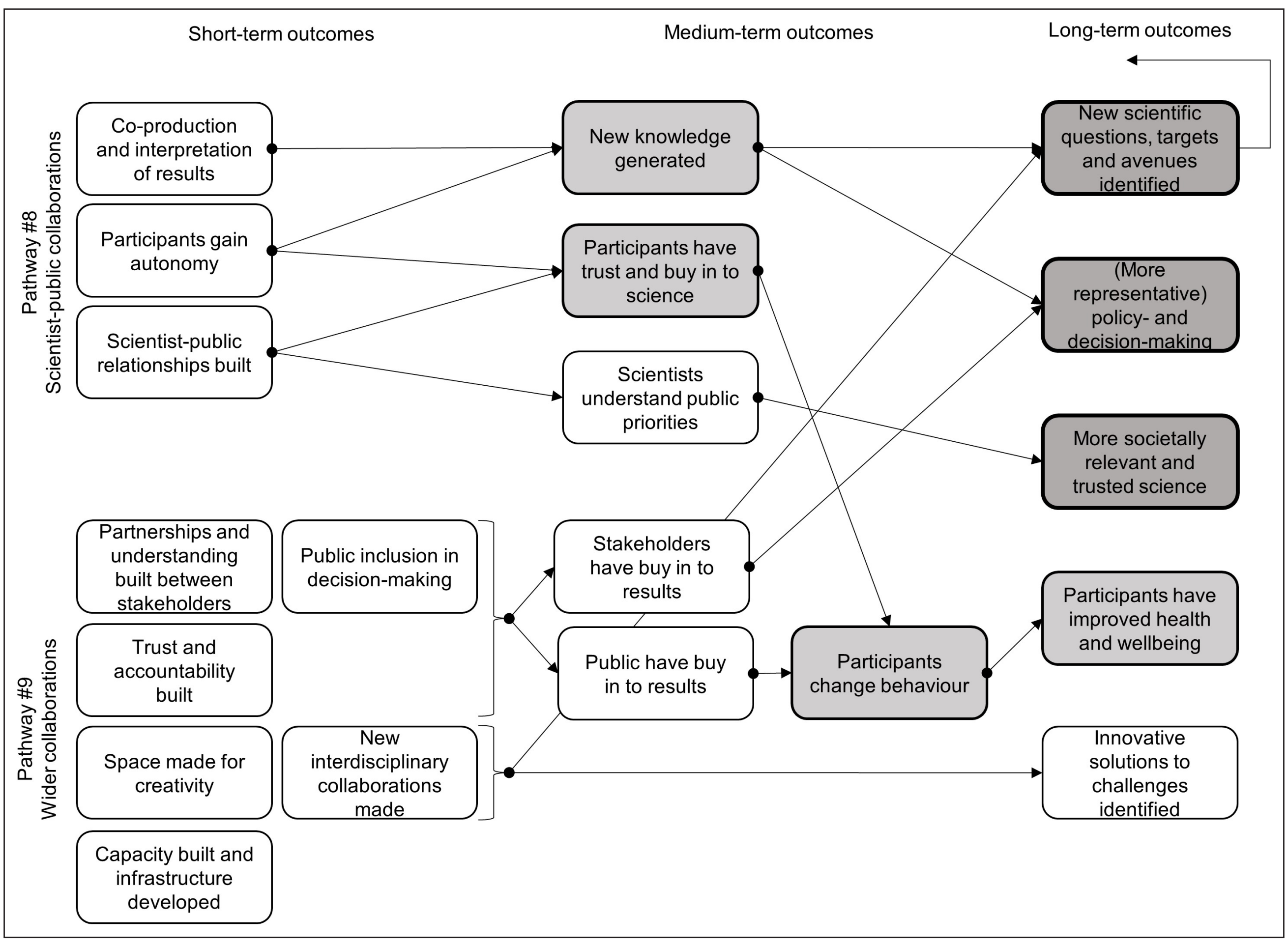

Figure 4 Collaboration pathways. Category appears in two pathway themes (*bold outline and light shading*). Category appears in three pathway themes (*heavy bold outline and heavy shading*).

Participant autonomy within the research process (rather than participants as subjects of research) and communication between scientists and citizens where it would not otherwise exist can also lead to better understanding of and relationships between these groups. By breaking down these barriers, it is hoped that, in the medium term, understanding of and trust in science by the public will be built, potentially leading to greater buy-in to science and its outcomes for behaviour change as outlined in the participant pathways above.

If two-way communication between scientists and citizens is fostered it can also lead to a greater appreciation by scientists of issues of importance to citizens and an openness to pursuing new research in these areas. In the long term, this could influence the research agenda and lead to more socially relevant and democratic science, in turn leading to decision-making that benefits society. Science that benefits society could further strengthen trust between the public and scientists.

Implications of lack of diversity for pathway 8

Where CS participants are not diverse and instead reflect exiting power structures in society, collaborations within projects reinforce not only whose experiences and perspectives are being heard, but also the structures within which decisions are made, and by extension the groups to which resources, including finance, are distributed. Opportunities to develop new research questions, ways of working, and research methods will be missed if collaborations do not include underrepresented groups. This limits CS's potential to democratise science because influence on research agendas will reflect the values of only those participating (Sauermann et al. 2020).

CS collaborations can play a role in building trust and understanding in science by opening up communication. Again, omitted groups will not gain this trust through participating in CS and so the resultant benefits for both science (buy-in to results and public support) and these potential participants (e.g., for personal decision-making) will be lost.

Pathway 9: wider partnership building

CS projects often include interested or influential parties beyond scientists and the public, including policy- or decision-makers, services providers, nongovernmental organisations, and businesses. In the short term, CS projects can act as a mechanism for establishing new collaborations and partnerships, leading to knowledge transfer and improved understanding between different stakeholders as well as increased trust and accountability between partners.

This engagement could lead to influential organisations having a greater understanding of, and trust in and buy-in to, the results of projects, which could increase the likelihood they use the results to inform decision-making or to take action, and also do so more rapidly than might otherwise occur. Inclusion of citizens and decision-makers in the same project could also lead to better decisions being made for the needs of the public, including traditionally marginalised communities, and greater buy-in from the public to those decisions, potentially leading to behaviour change and the resultant outcomes outlined above.

In the short term, CS projects can provide space for innovation and creativity that comes from bringing together diverse voices, including those from different scientific disciplines or different sectors. This could lead in the long term to the identification of new avenues for scientific research. A diversity of perspectives could also generate innovative ways of approaching understanding or solving problems, which could lead in the long term to improvements for the environment and society.

Finally, bringing together a range of stakeholders can help build capacity in different groups and organisations.

Implications of lack of diversity for pathway 9

This pathway highlights the opportunity CS presents for decision-makers to take differing perspectives into account. If some sectors of society are missing from these engagements, key issues that affect these groups will be missed, leading to a disparity in where research is focused (Sauermann et al. 2020) and which groups benefit from decisions taken.

Finally, while CS provides the opportunity to foster creativity, the extent to which this is achieved will be limited by the diversity of experiences and perspectives present. When considering the innovation of solutions to challenges, for example, Sauermann et al. (2020) note, "a diversity of knowledge inputs tends to increase the quality of solutions" (p. 6).

DISCUSSION

We have shown that, while CS has the potential to achieve myriad outcomes and impacts, when project participants are not representative of the wider population, these outcomes can further entrench disparities that exist in society. Unless CS projects can bring all voices to the fore, not just the wealthy, empowered, educated ones, then the places and people where change is most needed will continue to miss out. In writing this paper, while we found increasing numbers of publications describing the (lack of) diversity in CS participants, we found relatively few studies focused on the implications of this lack of diversity. More research is, therefore, needed to explore whether the implications we outline above hold true.

Based on the findings of this study, we make three key interlinked recommendations: 1) Use a pathways to impact approach to see cascading impacts of a lack of diversity, 2) consider how to increase diversity of participants, and 3) conduct evaluation to explore whether intended outcomes are occurring or not.

First, constructing pathways to impact has allowed us to describe the potential outcomes of CS and to track how a lack of diversity in participants can cascade through short-, medium- and long-term outcomes and contribute to a widening of inequalities in society. While the pathways we describe are a simplification of reality, which is actually substantially more complex, non-linear, and indirect, this method does provide a way for potential longer-term outcomes and impacts to be articulated, as well as the steps needed to achieve them. We recommend, therefore, that project designers create pathways to impact to describe intended outcomes of projects, taking care to articulate causal relationships between intermediary outcomes and impacts (Wehn et al. 2021) and to ensure they are aware of the interlinkages between different pathways and different temporal and spatial scales at which impact may occur (Wehn et al. 2021). Once these pathways have been developed, project designers should use them to think about how the diversity of participants their project engages might affect intended outcomes and impacts, using the suggestions resulting from our 9 pathways to help guide their thinking.

Second, project designers should carefully consider the range of barriers there may be to people participating in their projects, including less obvious ones: For example, indigenous peoples may participate less in CS not because of material barriers but because their ways of knowing are not recognised (Walajahi 2019). Unfortunately, however, little is currently known about barriers to participation and, crucially, less still about how these can be overcome. Different methods for recruiting and retaining participants should, therefore, be explored and tested within projects and experiences shared with the CS community to build a better understanding of how diversity can be increased, and give practitioners a range of options to try. One possibility is to think carefully about how and where people are recruited. For example, Sorensen et al. (2019) describe the value of attending neighbourhood events and hiring local champions to recruit participants and to share project findings. Motivations have been shown to differ between demographic groups (West, Pateman, and Dyke 2021), so appealing to a range of motivations may help attract more diverse participants. However, as the underlying causes of lack of diversity are likely to differ between contexts and types of project, methods for addressing this will differ. Pandya (2012) outlines a helpful framework for those wishing to increase the diversity of participants: aligning CS activities with community priorities, co-managing the project with community partners, engaging the community at each step of the project, incorporating multiple kinds of knowledge, and disseminating results widely.

Third, pathways to impact can play an important role in project evaluations, including for assessing the success or otherwise of efforts to widen participation. Evaluation is required to determine whether intended short- and medium-term outcomes actually take place, whether those outcomes lead to longer-term project goals, and whether any negative outcomes have resulted from projects (Walker, Smigaj, and Tani 2021). However, in many projects, there is still limited or no evaluation, with longer-term outcomes from CS particularly suffering from lack of evidence, with many projects relying instead on assumptions rather than empirical observations of outcomes (Bela et al. 2016). Increased use of evaluation tools, including to examine the diversity of participants and its consequences, and sharing of results will help to develop and improve the practice of CS. Those interested in measuring impact in CS may find Somerwill and Wehn (2022) and the MICS project (https://mics.tools) helpful for a review of the relevant approaches for evaluation.

CONCLUSION

Developing pathways to impact is a useful way to think through the cascading effects a lack of participant diversity can have on intended project impacts. We hope those designing CS projects are inspired to use a pathways to impact approach to think through how their intended outcomes can lead to impact, how lack of diversity of participants will influence outcomes and impacts, and how to increase diversity of participants. In conducting our review, we found limited studies that had robustly evaluated whether projects had achieved their outcomes. CS practitioners should conduct evaluation, particularly around whether or not they are inclusive of diverse participants and the consequences of this. Honest sharing of these evaluations and reflections on what works and what doesn't will help the CS field achieve the huge potential it has to have impact across many different domains.

DATA ACCESSIBILITY STATEMENT

Please see Supplemental File 1: Appendix A for a list of the 337 references from the literature review.

NOTES

1 UNESCO defines local and Indigenous knowledge as the understandings, skills, and philosophies developed by societies who have a long history of interacting with their surroundings. Traditional knowledge is a broader term referring to the knowledge held by communities, which are made up of those who may or may not be Indigenous. [https://en.unesco.org/links [last accessed 15th May 2023].

2 https://www.oxfordreference.com/display/10.1093/oi/authority.20110803114834542 [last accessed 15th May 2023].

3 https://www.ons.gov.uk/peoplepopulationandcommunity/educationandchildcare/bulletins/educationenglandandwales/census2021#:~:text=More%20than%203%20in%2010,%25%2C%20or%2016.4%20million%20people [last accessed 15th May 2023].

SUPPLEMENTARY FILES

The Supplementary files for this article can be found as follows:

- **Supplemental File 1.** Appendix A. The codes of benefits, outcomes and impacts arising from the literature review (as well as a brief description and example reference and quote) and the categories used in Figures 2–4 that they were derived from them. DOI: https://doi.org/10.5334/cstp.569.s1
- **Supplemental File 2.** Appendix B. A full list of the 337 references from which codes were derived. DOI: https://doi.org/10.5334/cstp.569.s2

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COMPETING INTERESTS

The authors have no competing interests to declare.

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