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Abstract | Citizen science is an increasingly acknowledged approach applied in many scientific domains, and particularly within the environmental and ecological sciences, in which non-professional participants contribute to data collection to advance scientific research. We present contributory citizen science as a valuable method to scientists and practitioners within the environmental and ecological sciences, focusing on the full life cycle of citizen science practice, from design to implementation, evaluation and data management. We highlight key issues in citizen science and how to address them, such as participant engagement and retention, data quality assurance and bias correction, as well as ethical considerations regarding data sharing. We also provide a range of examples to illustrate the diversity of applications, from biodiversity research and land cover assessment to forest health monitoring and marine pollution. The aspects of reproducibility and data sharing are considered, placing citizen science within an encompassing open science perspective. Finally, we discuss its limitations and challenges and present an outlook for the application of citizen science in multiple science domains.

Participants
A participant is a person who takes part in a citizen science project in a non-professional capacity, by helping to define its focus, gather or analyse data. Other terms used are contributor, volunteer or citizen scientist.

Lay knowledge
Lay knowledge comes from personal experience or tradition rather than formal education or professional research.

Indigenous knowledge
Understandings, skills and worldviews developed by societies with centuries to millennia of interactions with their natural surroundings, and with potential to inform decision-making about fundamental aspects of day-to-day life.

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Citizen science, broadly defined as public participation in scientific research and knowledge production, is becoming an increasingly well developed and valued approach with global reach and used in a wide range of scientific domains[1–3]. Much of this growth is driven by the availability of information technology infrastructures such as mobile phones and low-cost sensors for gathering and reporting data, the internet for sharing data, and cloud storage for hosting and storing data[4,5]. Growing literacy levels and educational attainment in many parts of the world also make it possible for many more people to contribute to knowledge creation in a meaningful way[6,7].

Citizen science initiatives involve the public in the research process to generate genuine scientific outcomes[8–11]. These outcomes include discoveries, such as in astrophysics[12] and archaeology projects[13]; new insights, such as in epidemiology[14] and socio-linguistics projects[15]; evidence-based policymaking, such as in pollution-monitoring initiatives[16–18]; interventions such as in public health research[19]; and environmental governance, including in ecology and biodiversity monitoring initiatives[20–22]. Citizen science research can fill important data gaps across both time and space[23], which might not otherwise be possible without the contribution of many participants, including people with local and lay knowledge[24,25] or Indigenous knowledge[26,27].

The profile of citizen science is also growing as a key pillar of open science, which encourages scientific collaborations that benefit both science and society, and which opens up the processes of scientific knowledge creation, evaluation and communication to societal actors beyond the professional scientific community[28]. The range of benefits that citizen science can deliver beyond scientific outcomes include societal impacts such as awareness of local issues and improved public health, policy impacts such as more effective legislation, political impacts including heightened civic participation, economic impacts such as higher-impact public spending and also personal benefits to the participants themselves, from the enjoyment of the activity itself, to new subject-matter knowledge and stronger scientific literacy more generally[29–32].

The field of citizen science is becoming more widely represented worldwide, including well-established regional networks, such as the European Citizen Science Association, the Citizen Science Association in the USA, the Australian Citizen Science Association and globally via the Citizen Science Global Partnership. Some of the key principles that underlie good practice have been encapsulated by an international community of practitioners in REF.[33] and the different factors that make up the unique aspects are described in REF.[34].

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The range of disciplines within which citizen science can be applied, as well as the diverse organizational and cultural contexts of those practices, has resulted in a wide range of terms that can all be captured under the wider citizen science umbrella. Examples include community science, participatory mapping, participatory science, community remote sensing, locally based monitoring and community-based monitoring[3,8,26,35]. It is also important to acknowledge ongoing contention regarding inclusive terminology when referring to citizen science participants in a way that recognizes the diverse expertise they bring and does not trivialize their contributions or exclude certain demographics[36,37]. For sake of consistency, we use the term 'participant' throughout this article. Additionally, seminal work in the field has developed typologies to describe activities in a range of ways, focusing, for example, on different models for public participation in scientific research[38], the levels of participation[35,39] or the orientation and aims of the activities[40]. Contributory citizen science, as presented in some of these typologies, mainly involves participants in data collection activities and is a prevalent approach used in the fields of environment and ecology[41].

Our focus in this Primer is on the application of citizen science approaches within the environmental and ecological sciences, where much of the recent growth in the field has taken place. Our main objective is to introduce contributory citizen science, as highlighted above, to scientists and practitioners who are new to the field. While we recognize the diversity of approaches and the wide range of possible applications, we limit our scope to contributory projects in the environmental and ecological sciences because they can provide a manageable entry point into citizen science practices, have a wealth of examples to draw on, and thus allow us to provide a more comprehensive overview and guidance on how to design and implement a citizen science initiative for the first time. We also intend the Primer to serve as a useful review and general resource for those who are experienced in the field.

Contributory citizen science
Citizen science programmes designed by professional scientists and involving primarily non-credentialled participants contributing to data collection.

Experimentation

In this section, we provide an overview of the different design and implementation stages of contributory citizen science projects in the field of ecology and environmental sciences, some of which will be described in more detail in subsequent sections. Various guidelines exist for designing and implementing citizen science projects, covering aspects from data management to stakeholder engagement[42–49]. Examples of such guidelines are presented in TABLE 1. Here, we summarize some of the most relevant issues and considerations from these resources and offer additional insights. Each of the stages presented in this section are interconnected and one step does not necessarily need to end for another to begin (FIG. 1). All stages and steps should be reviewed throughout the project cycle to actively incorporate changing factors, lessons learned and participant feedback. It is also essential to remember that there is no one-size-fits-all approach in citizen science and that these stages need to be adapted to the context of the project.

Stage 1

Stage 1 of the citizen science project life cycle is identifying the need or the problem, in which the need or the problem that the project is aiming to address is identified, and its boundaries are defined[38,48]. Depending on the purpose and type of project, the problem or need can be identified by scientists, participants, other stakeholders or all of them together, based on the models of public participation in scientific research[38] and the levels of participation[35,39].

At this stage, it is useful to think about the key stakeholders and try to understand the problem from their perspective — particularly stakeholders from target groups. Possible solutions to the problem and their limitations need to be considered, and research questions and general objectives should be formulated with reference to those solutions and limitations. Acknowledging that stakeholders may not have identified a specific problem or research question, as is sometimes the case in ecological and environmental studies, but instead may have noted the need for baseline monitoring, can help to guide the work.

Additionally, it is important to have an overview of similar projects and available methods that could be useful for the project. Within the rapidly growing citizen science field and literature, it is likely that similar problems and needs have already been addressed through other initiatives. Some early considerations on the evaluation and sustainability of the project are also helpful in framing the overall project idea and establishing a sound basis for the upcoming stages[48].

Stage 2

It is important to recognize that not all research projects can be addressed with the citizen science approach. This stage is about ensuring that citizen science is the right approach to address the problem and the research questions identified in the first stage[45]. The goal is to understand whether involving citizen science participants will help to achieve the desired results, while at the same time benefiting participants by addressing their needs

In situ
In situ refers to data that are gathered on a site, an activity that takes place locally, or an observation made at a specific location on the ground.

or fostering new skills and expertise[50]. If both those conditions can be met, then citizen science approaches are likely to be appropriate for the project[42].

Deciding whether citizen science is the right approach depends on various factors, such as the research questions, the spatial and temporal scale of the project, the type and amount of data needed to obtain results, the level of expertise required to collect the data, the training and coordination efforts needed, or the target groups of the project, such as the participants, policymakers, funders and scientific and practitioner communities[44]. Funding is a key consideration, and it is important to review the resources available and requirements for project objectives prior to starting[42]. This includes considerations related to human resources, including the skills that are needed in the team and the tasks and responsibilities of the project staff. Equipment, travel or training necessary for data collection should also be considered.

Examples of projects that are suitable for citizen science approaches are observing the natural environment, including wildlife and species; detecting changes in land use and land cover through in situ monitoring, where observations take place on site; classifying satellite images to identify deforestation; and monitoring water or air quality, or disease threats, among many others. Projects that may be unsuitable for citizen science approaches could be those that require the use of expensive or highly technical equipment, or projects that

Table 1 | **Examples of guidelines available for citizen science project design and implementation**

Title	Purpose	Related design and implementation stages
Biodiversa citizen science toolkit for biodiversity scientists[222]	Aiming to improve the understanding of citizen science practices and overcome potential barriers in research projects	All stages
Citizen science: a developing tool for expanding science knowledge and scientific literacy[38]	Describing a model for designing and implementing citizen science projects	All stages
Citizen Science For All: A Guide For Citizen Science Practitioners[57]	Providing guidance to those interested in initiating and participating in citizen science projects	All stages
Citizen science toolkit[48]	Providing basic processes for planning, designing and implementing a citizen science project	All stages
Choosing and using citizen science: a guide to when and how to use citizen science to monitor biodiversity and the environment[45]	Helping those who would like to design and implement citizen science projects in the fields of biodiversity and environment	Stage 1: identifying the need or the problem Stage 2: determining whether citizen science is the right approach
Communication in citizen science[223]	Providing a practical guide to communication and engagement in citizen science	Stage 4: building the community
Community-based Monitoring In The Arctic[35]	Sharing good practices in sustaining programmes, obtaining impacts, connecting with other approaches and addressing the rights of Indigenous communities	All stages
Data management guide for public participation in scientific research[43]	Introducing a step-by-step guideline to the data management life cycle for citizen science projects	Stage 5: managing the data
Data management planning for citizen science[187]	Making specific and practical recommendations to citizen science practitioners about the development of data management plans for citizen science projects	Stage 5: managing the data
Guide to citizen science: developing, implementing and evaluating citizen science to study biodiversity and the environment in the UK[42]	Presenting guidance and a decision framework for identifying whether citizen science is the right approach for a project idea	All stages
Handbook Of Citizen Science In Ecology And Conservation[47]	Providing guidance for planning and implementing citizen science programmes	All stages
Manaus Letter: recommendations for the participatory monitoring of biodiversity[46]	Guiding organizers of citizen science programmes about good practice in participatory monitoring of biodiversity and natural resource use	All stages
Stakeholder engagement handbook[224]	Offering practical guidance to researchers to better plan and engage with non-academic stakeholders, including policymakers	Stage 4: building the community
WeObserve Cookbook[225]	Especially designed for leaders of citizen science and citizen observatory projects, providing lessons on best practice, guiding users through resources such as tools, scientific papers, training materials and networks	All stages

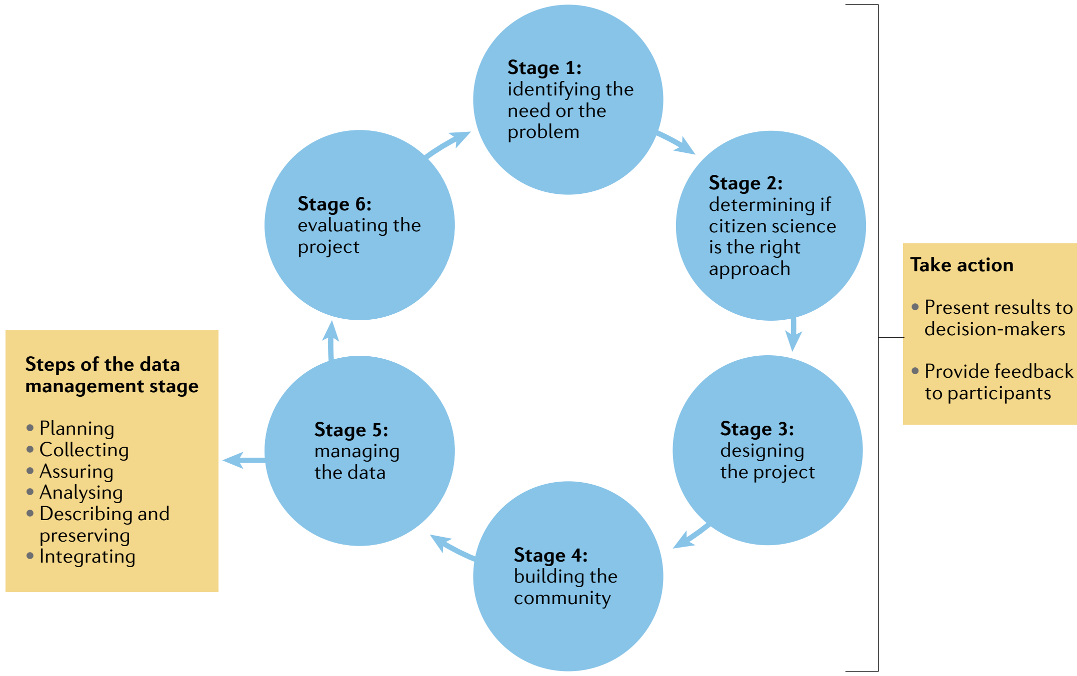


Fig. 1 | **Stages of designing and implementing a citizen science project in ecology and environmental sciences.** Six iterative stages of designing and implementing a citizen science project from identifying the need or the problem to evaluating the project, focusing on the fields of environmental sciences and ecology. Project teams should be action-oriented while designing and implementing citizen science initiatives.

demand a great deal of time commitment such as collecting detailed measurements every few hours or every day over a season[45].

Stage 3

In this design stage, the overall aims and objectives of the project need to be clearly defined in close collaboration with the prospective participants. For example, advocating for a policy change or collecting data to answer a scientific question or a combination of both can be the motivation for designing a citizen science project[51]. In many cases, practitioners may want to achieve additional outcomes that are beyond the intended results of the project, such as social learning, behavioural change or raised interest in science and community building; such outcomes should also be determined[1,2,52,53]. Defining the project objectives in detail will help to identify the data needs and data collection tools and formats, which could be a smartphone app or data sheets, among others. How these data should be collected — individually or in teams, with prior training or without — also depends on the project aims and objectives[48].

It is also important to identify whether similar data collection formats and methods are available and if reuse of existing data collection platforms is possible. TABLE 2 provides some examples of existing citizen science platforms for reuse. Where and how to store the data and for how long, and how to share them must also be considered in the design stage. These aspects are discussed in more detail in the reproducibility and data deposition section below.

Special consideration should be given to sampling design and the anticipated methods of data analysis. For example, depending on the project, participants may collect data opportunistically, without standardized sampling design, which may lead to oversampling of certain locations[48] and limited methods for data analyses. However, strategies such as providing additional incentives for visiting specific locations or areas, where no or very few data are available, or performing appropriate statistical analyses as part of the quality control process, among other measures, can help to avoid or reduce the impact of such problems[54,55]. Explicitly communicating the potential sampling biases to the audience will help to improve data quality and can increase the credibility and reuse potential of data[51,56].

Deliberate training strategies should be developed, considering online or on-site training and the hand-out of required materials such as how-to manuals and videos, among others. Defining potential participants and delineating a communication plan for participants and stakeholders, including the means and tools of communication, are also part of the design stage. Periodic newsletters, social media, scientific papers, podcasts, and a project website and forum are some examples of often used means of communication[48,57]. Furthermore, establishing partnerships with mass media such as newspapers, television channels or radio stations has been shown to be successful in increasing participation in citizen science[58].

Defining participant tasks in detail, identifying benefits to participants, and addressing individual safety issues related to data collection is also necessary. Decisions should be made about what learning outcomes or benefits for the participants will be provided, and how safety and liability concerns will be addressed.

For example, a project app can provide safety information when downloaded and platforms can offer educational tools even before the data collection activity takes place. Ideally, participant input should be considered when shaping these tasks and addressing safety issues, such that their needs can be continually assessed to allow for diversity and inclusion.

Stage 4

The next stage is developing a community building plan for the project. For successful community building, knowing the community and understanding their motivations for contributing time and skills for the project are important. Identifying the age groups, education levels and interests of the community members, among other information, helps in getting to know the community[48]. Motivation for participation can vary across community members and may include contributing to science generally and helping the environment, getting to know others with similar interests or gaining new skills. There is a vast literature on what motivates participants to join a citizen science project, which can provide insights and guidance[55,59–66].

At this stage, it is also important to consider ways to engage the community. This may be done online or through in-person workshops and meetings, depending on the type of project and the number of participants. In many cases, explicitly identifying the role of citizen science enablers will also help to ensure success. Citizen science enablers are facilitators or third parties who often bring skills and expertise in facilitation and communication, in public engagement or access to a community or to funding. These enablers or facilitators of the research may help to foster the relationships between all those involved, creating a stronger collaboration[67]. After engaging a community, sustaining participation in the project depends on how well the engagement strategies are designed and implemented. Engagement can also vary owing to factors outside the researcher's control. For example, studying environmental subjects or species that are not very popular may attract less attention.

Deciding on how to acknowledge the contributions of the community members to the project is also crucial[42,63] and should involve participants. This includes crediting individuals for their contributions, for example, by including them as co-authors in scientific publications or providing a visualization tool on the project website that shows participant contributions, which would have implications for the privacy policy of the project[68,69]. It is also necessary to acknowledge the contributions of partners and stakeholders to the project.

While creating a community building plan, it is important to be inclusive. Efforts should be made to ensure the participation of people with diverse backgrounds, ethnicities, income and education levels, and with varying access to and use of technology[36]. This is important not only from a social and environmental justice perspective, but also from a scientific standpoint, to prevent biases in data collection, to reach otherwise inaccessible or remote areas, increase geographical coverage and representation, as well as to address a broader range of stakeholder perspectives and networks[70–74].

Stage 5

This stage highlights the processes and steps related to data management, which may apply to any research project. However, the aspects presented here reflect the peculiarities of citizen science projects. These steps are not necessarily taken in sequential order: some may take place simultaneously, while others occur more than once[43]. The steps related to planning, collecting and assuring are presented in this section, whereas steps involving analysing, describing, preserving and integrating are discussed in subsequent sections.

Planning. In this step, a data management plan linked to the project design stage should be prepared, considering requirements such as laws and regulations regarding

Table 2 | **Examples of existing citizen science data collection platforms**

Platform	Description	Link
CitSci.org	A global citizen science support platform that provides tools to support an entire research process	https://www.citsci.org/
eBird	A platform that provides free web and mobile tools to collect and interpret bird sightings	https://ebird.org/
EpiCollect	A mobile app for collecting generic form data	https://five.epicollect.net/
GeoKey	A web-based platform for participatory mapping	https://geokey.org.uk/
iNaturalist	A platform that allows professionals, citizen science participants and others to collaborate on research, data collection, and monitoring and recording biodiversity observations	https://github.com/inaturalist/
Indicia	An open-source online recording toolkit that simplifies the building of biological recording websites and mobile applications	https://indicia-docs.readthedocs.io/en/latest/contents.html
iRecord	A site for managing and sharing wildlife records	https://irecord.org.uk/
Sensor Community	A contributor-driven global sensor network for open environmental data	https://sensor.community/en/
Zooniverse	A platform that offers an infrastructure for analysing large amounts of data with support from citizen science participants	https://www.zooniverse.org/
PISUNA-net	A searchable database of local observations and recommendations on natural resource management interventions, building on Indigenous and local knowledge	https://eloka-arctic.org/pisuna-net/en

data privacy and ownership, and policies relevant to data access and sharing. Additionally, it is critical to define ethical project practices, such as how to attribute contributions while at the same time ensuring privacy and documenting them through a clear set of terms of use and a privacy policy for the project, including which data will be shared and how[75]. It is also important to consider the sustainability of data management, to identify the associated costs and to ensure that resources are available to achieve successful data management.

In the planning step, it is also important to make the final decision on the types of observations needed to achieve the project aims and objectives. Examples of observation types are images, videos, sounds, water samples, sensor data (such as temperature and noise) or humans-as-sensors (to detect odours, for example) and interpretational data (such as identification and classification), among others[45]. While planning how to manage the data to ensure quality, the decisions made in the design stage related to sampling, participant training and evaluation should be reviewed and tailored according to the evolving project needs.

As part of planning, it is important to be clear about what data to collect and how to visualize these data, such as through graphs, summary tables or maps, to facilitate the interpretation of results. The project team should monitor the findings throughout the project and share these findings with participants and other target groups, while at the same time encouraging them to support the evaluation of these findings and communicating them to diverse audiences, including decision-makers.

Collecting. The collection step refers to the type of information needed to achieve the objectives of the project. This could be project-related information, such as observations of plants, trees and animals, as well as their locations and numbers, or additional information, such as the name, location and email address of the participants to ensure proper acknowledgement of participant contributions or data quality. It is important to consider the potential future use of data when deciding what type of observations and additional information to collect.

In ecology and environmental projects of the contributory type, data are mainly gathered using sensors, special equipment, standard protocols and opportunistically (where no standards or sampling methods are used), or through a combination of methods. While collecting observations, using a smartphone app can increase quality, since data such as location, date and time can be recorded automatically. However, this method of data collection may exclude those who do not have access to such technologies[66]. To ensure inclusiveness, printed data sheets and smartphones can be used in parallel to involve participants with diverse backgrounds and possibilities[48]. This step is also where training for data collection can be provided to ensure that the participants have all the information that they need to help to generate the required data.

Assuring. The assurance step involves ensuring the quality of data generated as part of the project. Data quality is related to its fitness for purpose, which means that the data are sound enough to be used for its intended purpose[76]. Data quality can be assured through quality assurance (QA) processes, which are implemented before and during data collection, and quality control (QC) processes, which take place after data collection. For example, providing training to participants or developing standard protocols for data collection are part of QA, and flagging outliers or checking photos submitted by participants are examples of QC[43,77]. These examples and additional ones are discussed in detail in the results section.

QA and QC processes need to be defined according to the aims and objectives of a project, but also its scale. Checking the quality of submissions by experts can be an option in a small-scale project but not on a broader one with thousands of participants. The QA and QC might bring in additional costs to the project, so resource implications should be considered. Clearly communicating the data quality, as well as the QA and QC processes, increases trust in the data and improves its reusability[78,79].

Stage 6

Evaluation is an essential step in any project including citizen science. There are various ways of evaluation, such as front-end evaluation for gathering baseline information, formative evaluation (conducted during implementation) and summative evaluation (usually implemented at the end of a project to identify its effectiveness)[42,80–82]. The best method of evaluation depends on the project, but it is recommended to consider evaluation as an ongoing effort, allowing improvement at any stage. In some cases, evaluation can be a funder requirement, along with identifying the short-term and long-term impacts of the project. Agreeing on metrics for measuring success, and for emerging and future potential impact, is key to a successful citizen science project[29,42,57]. New approaches to evaluation in citizen science projects are focusing on the individual-impact dimensions (in collaboration with participants) and the socioecological benefits, both worth considering when designing the evaluation methodology[83]. One example of this is the use of conservation management interventions emanating from citizen science projects as a proxy for their conservation impact[66].

Results

In this section, we provide examples of QA and QC approaches, including the training and testing of participants, community-based quality review, automatic control and statistical tools in contributory citizen science. We also provide examples of tools and methods to support data analysis in citizen science.

Training and testing participants constitutes one way to improve data quality[77] and is considered good practice[84,85]. Many projects offer online tools and training materials to improve the quality of participant observations, such as species identification guides or videos[86,87]. Some projects also provide customized feedback to participants based on expert validation as training to provide higher-quality contributions[55,88,89]. Additionally, training can occur through community consensus of

Table 3 | **Common concerns regarding citizen science data quality and common mitigation procedures**

Concerns related to	Examples of issues and concerns related to data quality	Mitigation procedures
Skills of the participants	Inconsistent application of the protocol, including physical loss of data	Training of participants before and during the project[77,84,226]; adapted guidelines[86]; expert control and filtering of data[96]; community-based validation[90,92]; automatic filtering and big data approaches[98,105,106]; evaluation of participants' skills[101]
	Inconsistent use of technical tools	
	Identification and translation mistakes	
	Observation, identification or systematic sampling bias (for example, cryptic species surveys)	Specific participant training or testing[86,94]; targeted expert validation[55,86,96]
Habits of participants	Unrepresentative sampling effort	Structured protocols with prescribed sampling in space and time[109,110]; data filtering and correction factors[23,107,112,115]; model-based integration[117]
	Bias or lack of neutrality	Mutual checking by professional scientists and participants on possible conflicts of interest[227,228]; triangulation across communities, participants and methods[66]

data, where data are cross-checked and validated by other participants[90].

Another approach to improving data quality involves testing participants' data collection and interpretation skills before or during the project, through quizzes and test-runs combined with tutorials, near-real-time expert feedback or community-based cross-checks and validation[90–92]. This can help in assessing data accuracy and supporting the project team to filter or weight the data on the basis of participant performance[77,93]. These tests can be complemented by asking participants to provide additional evidence related to their observations such as images[94]. Testing can also specifically target difficult-to-obtain data, including the identification of cryptic or rare species to evaluate participant skills[86]. Another approach is triangulation, in which multiple observers, methods and data sources are used to improve quality and overcome the biases that result from a single method, a single observer and a single data source[66,95].

Community-based data quality review, which may be conducted by dedicated experts or participants, is another approach to ensuring data quality. For example, projects using the iNaturalist platform (see TABLE 2) can designate experts as curators or managers, who can review the shared observations[96]. In parallel, iNaturalist allows observations to reach high reliability by providing a research grade through community consensus, which can also be an effective method of ensuring data quality[86,92]. Another approach is to designate participant-experts based on the quality of past observations. Participant-experts are participants who oversee the validation of observations recorded by other participants. This designation can be performed, for example, through an algorithm[92] or through self-designation of participants[97].

Data quality can also be improved through automatic control and statistical tools. For example, automatic filtering can help to flag observations that are outside the expected patterns[98]. Several statistical techniques have been proposed to ensure the quality of citizen science data[23,99,100]. These include inter-observer skill differences to correct bias in species distribution models[101,102], combining opportunistic data with data collected through sampling efforts[103] or pooling survey and collection data for many different species[104], among others. In some projects, automatic filters are used to verify the internal consistency of the datasets[105]. Project teams decide to make these adjustments on the basis of participant testing and the results of methods that assess data accuracy.

More sophisticated data science methods have also been used for improving quality in big data analyses[98,106]. In other cases, bias corrections are already integrated into the sampling tools and protocols. For example, REF.[107] collected anonymous geographical data to correct for biases caused by uneven sampling efforts from participants in the mobile app of a disease-carrying mosquito-monitoring project. TABLE 3 presents some of the issues and concerns related to citizen science data quality and frequently used methods of addressing them.

Analysing

Analysing the data generated by participants should be planned ahead according to the project goals and data needs. Various tools and methods exist to support data analysis in citizen science that depend heavily on the type of observations.

Spatio-temporal distribution of species and natural resources. Many citizen science projects from environmental and ecological sciences are designed to collect spatio-temporal distribution data for species or natural resources[32]. Data in these projects are usually analysed using qualitative or quantitative approaches. For example, qualitative methods are used in studies to represent the presence or absence of a given species in a certain area. Alternatively, spatio-temporal data can also be quantitatively analysed to generate patterns of abundance by counting the observed number of species of a given group, or individuals of a given species. Different types of analysis may be needed depending on the experimental design, which can be structured with prescribed sampling in space and time, semi-structured with minimal guidelines but inclusion of supplementary data added to each observation, or unstructured, providing opportunistic observations with no survey protocol being implemented[108].

Each type of design structure has different benefits and challenges that can be overcome with careful analysis. In the case of structured data, citizen science protocols may determine the spatial distribution and resolution of the observation sites, as well as the frequency of the observations[55,109]. These data may be used to assess species abundance along a transect[110] or within two-dimensional grids[111,112]. Structured data are commonly analysed using tools from environmental and ecological sciences, such as species distribution models[113] or ecological indicator design[114]. However, they are often taxonomically and geographically limited. On the other hand, unstructured data — such as opportunistic

Opportunistic data
Opportunistic data are gathered by participants, usually while being engaged in another activity, such as taking a walk. Data collection does not follow a structured sampling design and can therefore be unevenly distributed or contain biases.

Structured/semi-structured/unstructured
Citizen science programmes may be placed along a spectrum from structured to unstructured protocols. The level of structure of a protocol is defined both by the degree of prescription in space and time of the sampling effort and by the degree of training and experience of the participants.

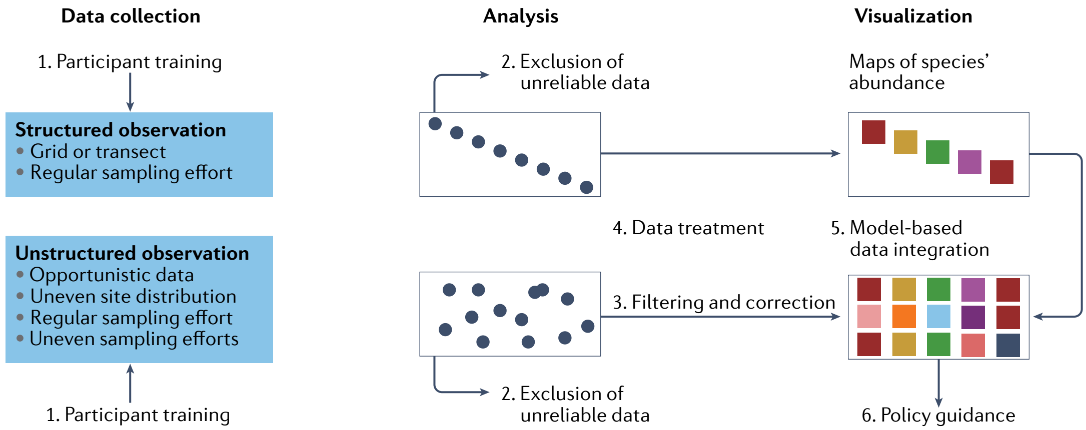


Fig. 2 | **Stylized citizen science quality assurance process for quantitative measures of species abundance.** After participant training (1), data can be collected through structured or unstructured observations. Structured observations are produced by protocols that determine the spatial distribution and resolution of the observation sites (for instance, along a transect), and/or the frequency of the observations. Unstructured observations (mostly opportunistic biological records) may need specific statistical tools to produce reliable abundance indices from individual observation efforts (3). In both cases, data are filtered to eliminate unreliable values (2) and treated to calculate other indices such as local species abundance or richness (4) and then modelled (5) for scientific research and visualized to guide conservation policies (6).

biological records — are generally collected in higher quantities, but specific statistical tools may be needed to render reliable abundance indices from individual observation efforts[115,116]. In REF.[23] a set of methods is proposed, based on data filtering or correction factors, to account for the variation in recorder activity and uneven observation sites. Model-based data integration has also emerged as a powerful way to combine heterogeneous datasets[117]. FIGURE 2 illustrates a stylized workflow for analysing quantitative measures of species abundance based on structured and unstructured data collection as part of citizen science projects monitoring biodiversity.

Dynamics of ecosystems. Citizen science data may also be analysed to study more complex dynamics of ecosystems, using statistical, computational or experimental tools. For example, citizen science data about insect abundances can be used to test spatial variations in insect–flower affinities by taking the total number of taxa recorded in the collections as a proxy for flower visitor richness[118]. Through the analysis of the occurrence of insects from different families on flowers of different morphologies, citizen science data can help to assess the role of floral morphology in flower-feeding[119].

Other citizen science data can be material samples, such as faecal pellets, leaves or soil samples[120]. These can be analysed following biological, chemical or physical laboratory protocols such as using visual interpretation keys, DNA extraction, amplification and sequencing[121,122]. Projects collecting such samples may blend the above-mentioned citizen science data analyses with common analytical tools such as those used in bioinformatics.

Data visualization is also key to initial understanding and exploration of citizen science data[123]. This can be done using open source software such as R or QGIS, or their (proprietary) counterparts like Stata, SAS and ArcGIS. These tools, as well as many others, such as the Data Visualization Overlay from the SPOTTERON citizen science platform, the CesiumJS open source JavaScript library[124] or the CWDAT open source tool[125] can be used to explore data, to formulate hypotheses and guide future research, to relate one's contributions to the whole dataset of the project or to identify data gaps[126]. Data visualization also allows participants to become more active in different steps of data collection and analysis[127].

Applications

The application of citizen science as a practice in the natural sciences dates to the beginnings of scientific inquiry itself and today spreads across the globe, leading to some of the longest-running time-series datasets in phenology, ornithology and meteorology[128,129]. In this section, we illustrate the diversity of applications of contributory citizen science with examples from biodiversity research, Earth observation and geography and climate change research, where citizen science has an established focus and can be considered a well-established method[3]. We complement these examples with applications that fall within the environmental domain but outside the box of contributory projects from the Global South, highlighting the potential and intricacies of community-led citizen science (BOX 1), as well as citizen science at the interface of education and environmental activism (BOX 2).

Biodiversity research

Biodiversity-related research is prevalent amongst citizen science projects[3]. Citizen science projects, at the same time, have become an important component of biodiversity research, both historically[130,131] and now[22]. For example, citizen science projects related to species monitoring have contributed at least 50% of the observations to international and global biodiversity databases, such as GBIF[132,133]. Despite this contribution, citizen science has at times remained unrecognized as a substantial contribution to these efforts[134]. One format

Community-led citizen science
Citizen science programmes involving members of the public and communities not only primarily as data collectors but also in additional stages of the research process (including identifying the question of interest, designing methodologies, interpreting data, and using data for decision-making), although professional scientists may provide advice and training.

Box 1 | **Community-led citizen science in ecology and environmental sciences**

When non-residents started seeking bushmeat in Itagutwa Village Forest in Tanzania, the inhabitants began monitoring the forest resources. "It shows them that this forest belongs to us," said a woman when asked why she kept track of the forest resources[60].

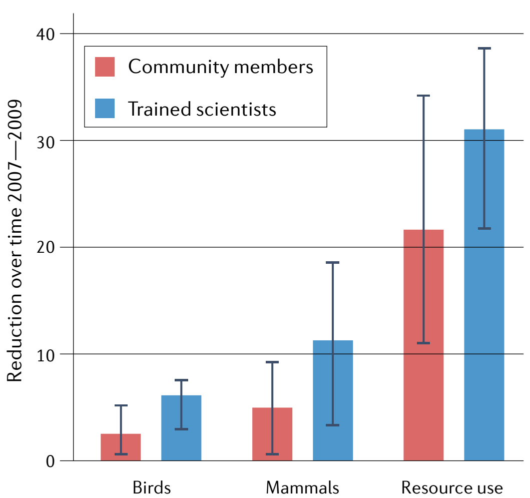
When members of the public are concerned about the environment and status of natural resources in an area, they sometimes want to lead and drive the research process related to their concern. Community-led citizen science (CCS) programmes involve members of the public in several stages of the research process beyond data collection, while professional scientists may provide advice and training[41,229].

CCS can be demanding in terms of the time and effort required of participants and scientists, but the potential benefits to those involved are substantial. The full-participation approach can provide time-specific and place-specific data at low cost that are trusted by those concerned and involved[230]. This approach can provide important natural resource management inputs. The approach can function as a vehicle for continual engagement between local communities and scientists, improving the communities' scientific understanding and the feeling of being heard and acknowledged[24]. Moreover, CCS can help to generate transparency, accountability and local ownership of resource management initiatives, empowering community members and prompting locally meaningful actions[66,231].

CCS programmes require ecological and sound facilitation expertise from researchers, careful consideration and long-term planning. The approach is used in the Global South[205] and the Global North[232], including the Arctic[233], in environmental justice[234] and other community-based initiatives. The Community-based Monitoring Library provides best-practice examples from the Arctic and lessons learnt for practitioners. CCS is particularly suitable where policy environments allow full or partial community control over resource management[66]. Programmes involving Indigenous communities may benefit from Indigenous knowledge[24], using Indigenous indicators[235] or scientific methods adapted to non-specialist use[236]. Triangulation across communities, community members and methods can optimize sampling accuracy[66]. Data management should protect sensitive personal data and respect local data ownership and Indigenous knowledge sovereignty[95].

Challenges sometimes faced by CCS programmes include the following: getting authorities to respond to data and proposals and overcoming their reluctance to relinquish authority[237]; ensuring collective action and public participation[164], particularly when programmes are driven by external research and not by the communities themselves[238]; or addressing perceptions of scientists that participant data are unreliable, which can hinder the use of the results[239], despite demonstration across many ecosystems and socio-political settings[85] that citizen science can provide reliable information and results (for example, on the status of and trends in the abundance of species and information on natural resources). Disturbingly, participants engaging in CCS and associated advocacy are also being increasingly persecuted[165,240]. Between 2002 and 2020, more than 2,200 people have been reported killed, mostly in countries with authoritarian rule, for defending their lands and the environment[241]; some were killed while monitoring the environment and the status of the natural resources[165]. Researchers engaging in CCS must take such sensitivities, risks and challenges into account.

Comparison of community member and trained scientist observations[66,85]



Error bars represent the standard error. Image reprinted from REF.[66], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

for a biodiversity-focused, contributory citizen science activity that has gained popularity and traction in recent years is the BioBlitz. The Great Southern BioBlitz includes more than 270 local and regional initiatives in the Southern Hemisphere contributing over 190,000 biodiversity observations across the Southern Hemisphere in 2021. Citizen science presents vast opportunities for applications in biodiversity research, including improving undersampled taxa and regions in the Arctic and the Global South[35,74,85,135,136], making extended use of secondary, image-based data to infer relational ecological information or for automated abundance modelling using regularly updated citizen science data[137]. We illustrate the use of citizen science for species diversity, abundance, distribution and habitat research with three examples: MammalWeb, Spipoll and the Participatory Guide of the Marine Species in the Barcelona Metropolitan Area.

MammalWeb. MammalWeb began in 2015 in northeast England, UK, and has expanded to engage participants in many European countries. It applies a contributory citizen science approach to wildlife monitoring to fill data gaps in mammal biodiversity and distribution[138]. To join the project, participants provide their own motion-triggered camera traps or borrow one from MammalWeb and deploy these cameras for observations (Supplementary Fig. 1). Collected photos and videos are uploaded with spatio-temporal metadata to MammalWeb and classified by registered users. Images of humans are removed from the classification pool immediately after being flagged. Multiple classifications are obtained for each photo and video sequence, and a subset of the data is classified by subject experts. These two groups of classifications can be aggregated into consensus classifications with confidence levels[139]. Timestamps from the camera trap observations enable profiling of the daily and seasonal temporal patterns of various species. Analyses of the spatial data have improved understanding of the diversity and distribution of wild mammals, revealing temporal patterns in animal behaviour, and may aid future analyses and estimations of population structure through occupancy modelling[140]. The dataset is also designed to train machine learning algorithms for automated wildlife recognition[141].

Other conservation organizations are now hosting camera trapping projects on MammalWeb. This expands the geographical coverage, decentralizes the organization of participants and reveals its potential to stimulate engagement through the novelty of new wildlife observed. MammalWeb was also introduced to a local secondary school where students designed and implemented associated engagement activities[142] and led a professionally produced documentary[143].

Over 270 participants across eight European countries have contributed data to MammalWeb. The network includes more than 50 schools and 20 additional organizations. Participants have contributed over 340 years of cumulative observation time, collecting more than 620,000 photo/video sequences and approximately 2 million photos. Participants have helped to locate potentially invasive species including raccoons and coati[144].

Box 2 | **Collaborative Creation of Scientific Knowledge**

The Cientificos de la Basura (Litter Scientists) programme is a research alliance between marine scientists, schoolteachers and schoolchildren from Chile and other Latin American countries, investigating the extent and the causes of marine litter. It is a contributory citizen science programme with a strong focus on education and environmental protection[242]. Each school year one research topic is identified, such as type of macrolitter or microplastics on beaches, litter in rivers or interactions between litter and organisms. Several learning modules introduce the aquatic environment, ecological relationships, anthropogenic threats and the scientific method. Specifically designed educational materials present the topic and motivate a specific research question. Standardized sampling methods are carefully introduced[242] and applied by schoolchildren who assume specific roles during the research activity and work in small teams (Supplementary Fig. 4). In a follow-up classroom activity, they evaluate their own data and interpret their findings. They are also encouraged to communicate their findings within their community and implement small, local mitigation actions. The schoolchildren know they are part of a wider scientific investigation on an important environmental problem and this knowledge can be highly motivating to them[243]. However, participation in the citizen science activities had only limited effects on science literacy and pro-environmental behaviour, and it is emphasized that these activities should be part of wider and more integral programmes fostering scientific learning and promoting environmental stewardship[244,245].

The schoolteachers are the principal allies in the programme; they are regularly trained by the professional scientists and personal communication is maintained throughout the programme's activities. Teachers also submit the observations to the scientific team and are first to receive the collective results, ideally in a timely fashion so that they can share them with the schoolchildren who participated in the research. The scientific team also evaluates the data to answer the scientific questions, interprets the findings, prepares them for scientific publication and shares them with decision-makers and with the public via media outlets[246–248].

The data have contributed to formulating or improving national laws on waste management[249]. Data are validated and curated by the scientific team and are made available upon request, as are also all the educational and scientific materials. The approach of the Cientificos de la Basura programme has been replicated in Germany[250,251], where the sister programme — Plastic Pirates — is currently expanding to work with schools from other European countries.

Engagement with nature through MammalWeb has improved the mental health of student participants, especially during the COVID-19 pandemic[145]. Some MammalWeb participants have independently initiated multiple community-led spin-off projects including one leading to the declaration of a local nature reserve[146]. Key insights for contributory citizen science include increased recognition of the value of partnering with organizations and schools to expand data coverage and engagement, advanced understanding of statistical modelling of human classifications to improve the accuracy of the data obtained as well as the realization that the most engaged participants are highly motivated and move towards co-created citizen science, a development that should be welcomed by scientists.

Spipoll. The Photographic Survey of Flower Visitors, Spipoll, was launched in 2010 by the French National Museum of Natural History (MNHN) and the Office for Entomological Information (OPIE) to study the changes in plant pollinator interactions in space and time across France[147]. Participants follow a standardized protocol, which does not require any prior knowledge about insects. Wherever participants find a flowering plant — from dense urban centres to natural areas — they photograph all invertebrates landing on its flowers during a 20-minute period. After having identified insects and plants using a dedicated online identification tool, participants upload their photographs and associated identifications, as well as the date, time and location of observations and climatic conditions to the Spipoll website. Quality control was originally exclusively made by expert entomologists, who validated insect identification; however, since 2019, a collaborative quality control system has been implemented, which now allows participants to validate observations submitted by others (Supplementary Fig. 2). Datasets are analysed to quantify visiting insect communities, depending on the flower family and environmental factors. These results are then interpreted in terms of plant–insect interaction characteristics as a function of time and environmental factors, such as affinities with the urban and natural land use of the frequent and infrequent taxa within several insect orders[118,148].

To ensure the long-term engagement of participants, yearly meetings are organized with researchers from MNHN and community managers from OPIE. Weekly news, scientific results and other information are shared on the project website, and a monthly newsletter is sent to participants providing information on overall progress. Additionally, participants can comment on observations from others on a dedicated website, leading to the emergence of a social network, which promotes scientific learning, increases data quality and contributes to community building[97].

Data from Spipoll have led to new scientific knowledge on the effects of urbanization on community composition[118,119], contrasted affinities of pollinators with different land use[147] and the role of domestic gardens as favourable pollinator habitats[148]. Datasets are available under open access licenses. Spipoll's online communication spaces for participants contribute greatly to the constitution of a friendly learning community, assist with long-term retention of participants and help to improve data quality[97]. As such, Spipoll illustrates the key role of such online interaction and participant support tools in achieving the multiple goals of contributory citizen science.

Participatory Guide of the Marine Species in the Barcelona Metropolitan Area. Conserving biodiversity near urban beaches is challenged by the increases in anthropogenic and climatic impacts. The Participatory Guide of the Marine Species in the Barcelona Metropolitan Area project (URBAMAR), a collaboration between an academic institution, the Institute of Marine Sciences (ICM) and a private company, Anellides Environmental Services, engages participants to monitor and understand the factors affecting biodiversity in beaches around the Barcelona Metropolitan Area. Observations are collected mainly during guided snorkelling tours offered by Anellides Environmental Services, which provides local knowledge and logistics support, such as masks and underwater cameras. Photographs collected during snorkelling events are then added to an online project platform that allows participants to share the observations for comments, identification and collaborative validation. The community-based validations are then reviewed by the ICM data curator. Data are analysed by the ICM researchers to identify differences in the

BioBlitz
A collective activity, most often open to the public, to record biodiversity observations within a set time frame and within a defined spatial area, often also combined with expert talks and hands-on activities.

Metadata
Metadata help to identify basic information about data regarding when, where and how the data were gathered, for what purpose, what information they include and how the data quality was ensured, among others.

Bottom-up
Self-organized, people-led initiatives, often forming around matters of local concern or shared interest.

OpenStreetMap
The Wikipedia of maps — a free and open digital map of the world, created by volunteers.

composition of ecological communities and to link those to the anthropogenic impacts. The first estimation of species richness[149] was obtained with an approach based on unique observations and the species list[150].

The project has been promoted particularly through the social channels of the Anellides Environmental Services, exploiting the guided scientific snorkelling tours as a market opportunity. Most of the participants did not have prior knowledge of marine organisms. Tours with guided specialists ensured the correct use of equipment and safety conditions, as well as the most suitable places to explore depending on the sea conditions (Supplementary Fig. 1). In some cases, they also provide innovative learning activities for schools[151].

The project has led to the first Participatory Guide of Marine Biodiversity in the Barcelona Metropolitan area[152] and helped to provide a baseline dataset for the unknown extent of marine biodiversity in urban coastal waters of Barcelona. The Barcelona City Council has included part of the results as a new marine component, a fish species layer, in its Atlas of Barcelona Biodiversity. The project provides a successful example of the Quintuple Helix innovation model applied in citizen science with the participation of academia, industry, government and civil society[153]. The engagement of different actors — and of volunteering participants in particular — has facilitated a new societal perception of the marine biodiversity in the urban environment which may affect future policies of coastal management in the city. This highlights the collective impact contributory citizen science can have.

Earth observation and geography

In the areas of Earth observation and geography, the practice of citizen science appears under different terms. These include volunteered geographical information[154], crowdsourced geographical information[155] and most recently, geographical citizen science[156]. In this area, applications range from bottom-up projects, such as OpenStreetMap, in which hundreds of thousands of participants create a free and open map of the world[157], to projects led by scientists supporting extended networks of seismographs in regions susceptible to landslides and earthquakes but poorly covered by seismic stations[158]. We exemplify the application of citizen science in earth observation and geography with the FotoQuest Go project for research on land use and land cover change.

FotoQuest Go. FotoQuest Go aims to collect ground-based observations on land use and land cover across Europe. A specific aim was to identify whether citizen science participants can collect observations as high quality as those collected by professionals at a lower cost and at higher temporal and spatial frequency, to complement the Land Use/Cover Area frame Survey (LUCAS), a professional survey conducted by EuroStat on land use and land cover across the EU every three years[159]. Participants are prompted to visit specific locations provided in the FotoQuest Go app, take photos and answer questions about how the land is used at that location. Additionally, the FotoQuest Go app collects personal data such as name, age, gender, email and the location, time and date of observations. When a participant submits an observation, professional scientists check the quality, comparing it to the LUCAS data using the FotoQuest Go Near-real Time Feedback Tool[55]. The tool allows scientists to send customized messages to participants about the quality of their submission and how it can be improved. Short training videos provide information on how the app works, how the participants can make and submit quality observations and how to identify different crop types to further improve data quality (Supplementary Fig. 1).

FotoQuest encourages each participant to visit several locations. This implies that observations provided by the same participant are not independent of each other. Simultaneously, the closer the locations are to each other, the higher the spatial autocorrelation. To acknowledge the lack of independence of the data, generalized linear mixed models were used, including random effects for participant and location. The models were employed to match the data collected in FotoQuest Go to the reference data, LUCAS. All model assumptions were checked on the residuals[55,160].

Social media is used intensively to engage with the participants. The project website includes a forum to enable communication between the scientists and participants and among participants. Additionally, in the 2018 FotoQuest Go campaign, each successful submission was awarded a monetary compensation of €1–3, based on the distance of the visited location to the nearest road. The privacy policy of FotoQuest Go, accessible via the project website and the mobile app, explicitly states why personal and other information is collected, how it is stored and used and how it can be retrieved. Additionally, FotoQuest Go was designed to be compliant with the EU General Data Protection Regulation (GDPR), based on professional legal advice[161].

The 2018 FotoQuest Go campaign results showed that FotoQuest can complement LUCAS by enabling continuous collection of large amounts of high quality and higher density in situ data at a much lower cost than the official LUCAS data[55], showcasing the economic as well as scientific benefits that contributory citizen science can have. Data from FotoQuest Go are open and freely available in IIASA's Data Repository, and in the form of an open access academic paper[55]. Furthermore, FotoQuest Go illustrates how gamification elements, targeted incentive schemes and direct expert feedback can affect participant motivations and behaviour as well as data quantity and quality.

Climate change research

Citizen science is also widely used in research on climate change mitigation[162,163], adaptation[164,165], effects and impacts[166,167]. Citizen science is being applied across many topics, including — but not limited to — investigating soil moisture[120], groundwater[168], flood levels[169], sea ice[170], snow depth[35] and snow algae blooms and observing changes in local phenological patterns[171], bird migration[116], cloud formation[172] or coral reef damage[173]. Data collection and analysis, as well as target audience and engagement methods vary widely, depending on the respective topic and research questions. We illustrate the use of citizen science in plant ecology for forest-related climate change research where projects have studied the effects of climate change through phenology patterns[174], distribution shifts[175] and responses to novel wildfire events[176], among others.

Western Redcedar Dieback Map. The Western Redcedar Dieback Map (WRDM) project was launched in Washington State, USA, as the pilot project of the Forest Health Watch program. It was designed to engage participants to accelerate research and create shared understanding about the dieback of western redcedar trees. The project was co-designed with researchers from state and federal agencies to reveal the distribution of unhealthy trees and the general patterns of dieback in relation to climate change. It aims to identify important environmental factors (like climate, soils and topographical data) to classify trees as healthy or unhealthy. WRDM was launched on iNaturalist because of its accessibility and usability features (allowing any user to export data), the stability and usability of the mobile application, the built-in support for community agreement as quality control for species identifications and the robust existing user community. iNaturalist users contribute to the project by sharing observations that include photos for identifying the tree species, answers to custom questions and GPS coordinates. These coordinates were applied to collect additional environmental data, such as climate data using the ClimateNA tool[177] and soil data from the SSURGO database[178]. Data shared on iNaturalist are combined with ancillary environmental data to explore the factors associated with the health of the western redcedar using a random forest classification algorithm. The collection of both healthy and unhealthy tree observations helped to overcome a common challenge of biodiversity studies, namely the documentation of the absence of an organism with confidence[179].

The Forest Health Watch programme recruited participants through presentations and retained interest by hosting monthly research updates to add transparency, brainstorm project improvements and to discuss data and updates about the project's progress. Many participants were first-time users on iNaturalist, joining the platform out of interest in accelerating research about the dieback of the western redcedar. Some participants were recruited directly through iNaturalist by commenting on relevant observations outside the project. Overall, the recruitment and retention activities were time-intensive, and the dedication needed to engage participants should not be underestimated.

Citizen science can provide valuable complementary data for climate change research, especially where ancillary environmental data exist. The WRDM project provides an example of an approach to combine environmental data with empirical data collected via iNaturalist in a contributory citizen science project. As of April 2022, more than 1,400 observations from almost 200 participants were collected for the WRDM project (Supplementary Fig. 3). The tree health assessments by citizen science participants were critical for identifying environmental predictors of western redcedar dieback. The approach used within this study can be implemented in other contributory citizen science projects designed to study the relationships between environmental factors and organisms.

Reproducibility and data deposition

Describing and preserving data are essential for their discovery, reproducibility and reuse. Here, we discuss aspects related to reproducibility and reuse and provide recommendations on how to preserve data. Additionally, we discuss integrating data from contributory citizen science with other sources of data to help tackle complex societal issues.

Describing and preserving

Data and other outputs from citizen science should be described, documented and shared with permissions to ensure reuse and reproducibility[180], but it is important to consider what data to share and how to share them[133]. For example, sharing the precise location of endangered species might inadvertently aid illegal poaching. Sharing of citizen science data also poses ethical issues regarding the data privacy[181] and the data sovereignty of individual participants, which means that the participants have the right to take complete control over their own data[35]. Solutions include lowering the resolution of coordinates in spatial data or obscuring personally identifiable information, both of which help data sharing to serve multiple scientific and policy-related purposes while maintaining participant privacy. These purposes include characterizing the spatial change of natural resources with global changes[111] including in poorly sampled regions of the world[137], modelling species extinction[182], assessing modifications of biological community composition[112] and training machine learning algorithms[183]. Additional outcomes of sharing data openly include informing policies, such as in biodiversity conservation by influencing the delimitation of conservation zones, identifying illegal fishing or hunting practices[110], assessing the impact of conservation policies and participating in official monitoring of natural resources[32].

Describing the data — referred to as metadata — is essential to facilitate data sharing and reuse. There are various metadata standards that can be used in citizen science. For example, Public Participation in Scientific Research (PPSR) Core is a set of metadata standards developed particularly for citizen science, and Darwin Core is a standard that aims to facilitate biodiversity information sharing[184]. Using a known metadata standard can help to maximize the value of the data by offering a common format for data storing, description, and interoperability and integration with other datasets. Rich metadata and data practices also support FAIR (findable, accessible, interoperable and reusable) data principles, as well as the ECSA ten principles of citizen science and ECSA's characteristics of citizen science[33,34,185].

Protecting sensitive citizen data and respecting local data ownership and Indigenous knowledge sovereignty are important aspects of data management for citizen science programmes[35,95]. The CARE principles (collective benefit, authority to control, responsibility and ethics) for Indigenous data governance offer a framework

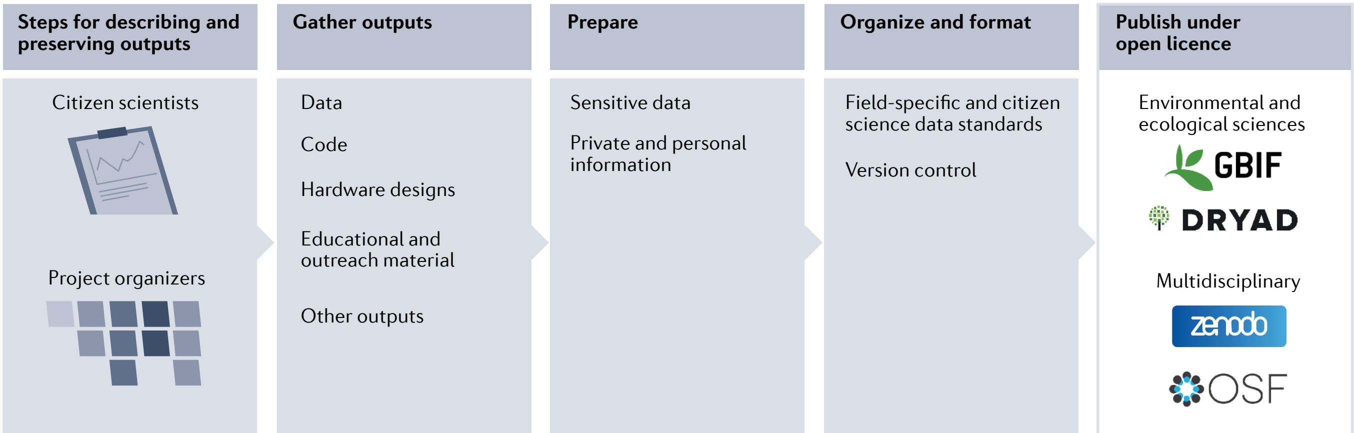


Fig. 3 | **Best practice for publishing outputs from a citizen science project.** The steps depicted fall within the describing and preserving data step in Stage 5 of a citizen science project plan: gathering outputs, pre-publishing preparation, organizing and formatting outputs and publishing in long-term repositories. Input from participants should be sought when creating and implementing the plan. GBIF logo reprinted with permission from GBIF (https://www.gbif.org). Dryad logo reprinted with permission from Dryad (https://datadryad.org/stash). Zenodo logo reprinted with permission from Zenodo (https://help.zenodo.org/). OSF logo reprinted from OSF, CC0 1.0 Universal (https://creativecommons.org/publicdomain/zero/1.0/).

for supporting Indigenous data goals that complements global efforts to advance open data[186]. Additionally, it is important to highlight that citizen science projects inherently involve diverse participants and should apply ethical publishing practices[181,187,188]. It is also good practice to involve participants when designing the data management plan, such as in deciding how attribution is given. FIGURE 3 illustrates the process for publishing outputs from a citizen science project.

Equally important are software and hardware outputs. Reproducible code best practice should be followed, as demonstrated by The Zooniverse and iNaturalist, which publish the complete source code of their servers and mobile applications on GitHub[189]. The process is similar for hardware designs[190].

All outputs — such as data, software, hardware and others — should be published in a dedicated data repository. For environmental and ecological sciences, this could be the GBIF or Dryad. Multidisciplinary repositories such as OSF or Zenodo are also appropriate. These repositories provide a Digital Object Identifier (DOI), which allows a dataset to have a permanent citable reference. The Registry of Research Data Repositories provides a list of additional data repositories[187]. While software and hardware design often occur on version control platforms such as GitLab or GitHub, copies should be deposited in these repositories. The Cos4Cloud project hosts various online services to aid citizen science data interoperability and reproducibility for uptake into the European Open Science Cloud.

Open licenses should apply to all outputs, which formally grant users the permissions for reuse mentioned above. The website choosealicense.com provides guidance for software, and the CERN Open Hardware Licences apply to hardware designs. The Creative Commons Attribution (CC BY), Attribution-ShareAlike (CC BY-SA) licences or the public domain dedication (CC0) are typically used for data and other publications, such as the educational material accompanying the Snapshot Safari project[191]. Citizen science projects should ideally publish all their outputs in this way, not just data.

Integrating

Data integration is about combining data from various citizen science projects or combining citizen science data with other sources of data for addressing complex research questions and issues[43]. For example, the Global Earth Challenge Marine Litter Data Integration Platform harmonizes and publishes citizen science data on beach and shoreline litter collected through three citizen science initiatives, the National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Monitoring and Assessment Project's Accumulation Data, the European Environment Agency's Marine Litter Watch, and the Ocean Conservancy's International Coastal Cleanup (ICC) Trash Information and Data for Education and Solutions (TIDES) database[192]. Picture Pile, a web-based and mobile citizen science application for ingesting imagery from satellites, orthophotos, unmanned aerial vehicles or geotagged photographs that can be rapidly classified by participants, combines Earth observation and citizen science data for environmental monitoring[193]. Providing a detailed data description using standard methodologies can support successful data integration.

Limitations and optimizations

Citizen science has several limitations, including the wide range of required skills outside the research subject, sustaining engagement, biases related to data collection and analysis, sensor calibration issues and varying data privacy regulations around the world, among others. In this section, we elaborate on some of these limitations and give examples of potential solutions.

Designing and implementing citizen science projects require a unique set of skills and knowledge outside the research itself, such as communication planning and execution, community building and participant management. Gathering these skills may require substantial investment depending on the project and the expectations of participants. Using free-of-charge or low-cost software and establishing partnerships with other project teams and stakeholders conducting similar activities can help reduce some of these costs[42].

Lack of participant engagement can be another limitation. In some cases, this could be design-related, which is within the control of the project team[62]. In other cases, it can be out of the control of the project team (such as when the intended research subject is not interesting to the target audience). Additionally, in some contexts with high social inequality, citizen science may engage only certain parts of society, which may potentially fail to include historically underrepresented groups, less-affluent members of society and individuals and communities from certain socioeconomic, racial and ethnic groups. This raises concerns about the relevance of citizen science to diverse communities and may affect the quality of results by excluding important perspectives in the projects[70,194]. It is important to understand participant motivations at the design stage, to create tasks that appeal to different motivations, to ensure that these tasks match participant expectations, to facilitate participant feedback and exchange throughout the project, as well as to integrate co-design processes in the project depending on the availability of time, resources and necessary skills[62,195,196].

All scientific data — including data obtained using citizen science — is subject to biases. It is important to be aware of these biases and work to mitigate them through attentive design and data analysis. A common bias in citizen science is related to whether or not non-professional participants can produce accurate datasets. As discussed previously, there are various approaches that can ensure data quality through iterative project design and implementation, and there is a growing literature demonstrating that citizen science projects can produce reliable data that are comparable with those produced by professional scientists[55,77,79,85,197].

Another form of bias in citizen science relates to population density; areas with larger populations are likely to be monitored more frequently[198]. Road networks also have an impact on which locations can be easily accessed and monitored[199]. There are also temporal biases caused by higher rates of monitoring during daytime hours and weekends[56,200,201]. Additionally, there are common biases related to participant contributions, where a relatively small number of participants provides a substantial proportion of the data[202]. Participant demographics — including education level, age and gender — can influence the coverage and wider impact of a project[203].

When making sensor-based observations, citizen science projects will mostly use low-cost sensors, frequently those that are integrated into smartphones or that are appropriated from other purposes (such as automotive applications). The limitations and biases of these sensors need to be addressed within the context of their purpose in the study, such as raising awareness on a particular issue within a community or contributing to policymaking, among others[204]. Existing literature can help to identify and solve these sources of bias.

Varying data protection laws in different countries is another major limitation in the adoption of citizen science. When deciding which data to collect and share within a project, it is important to identify and comply with the relevant laws and regulations of the country or countries in which the project operates. Considering what data are essential for the project at the design stage of a project is recommended. For example, the European Union General Data Protection Regulation prescribes the data minimization principle, which means data collection must be limited to what is necessary in relation to the purposes for which they are processed and must be kept as long as needed[161].

Data minimization
The collection and processing of only as much data as is absolutely necessary for the purposes specified.

Additionally, there may be limitations related to designing and implementing citizen science projects in remote and unsafe areas, where crime levels are high and political risks exist, or where mobile network coverage is poor, access to smartphones and electricity is low and illiteracy levels among participants are high. Co-design and community-based approaches can address such challenges and ensure a high level of participant engagement[205] (BOX 1).

Finally, risks related to data collection can also be a limitation in citizen science. For example, if the project requires participants to visit specific locations to make observations, the potential risks to the participants should be considered and clearly communicated to them along with information on how to avoid these risks. TABLE 4 provides a list of potential limitations of citizen science and strategies to overcome them.

Outlook

The fields of application for citizen science methods and approaches continue to broaden in terms of subject matter and deepen in terms of improved methodologies. More examples of citizen science research are entering the mainstream scientific literature. The principles described in this paper have been successfully applied to a wide range of research domains, which in turn contribute further to the development of both best practice and novel approaches within the ecological and environmental sciences[206,207].

Centralized training and knowledge sharing within research performing organizations is helping to diffuse citizen science practices across disciplines, such as at the Citizen Science Center at the University of Zurich, opening up new opportunities for transdisciplinary research. Practitioner-oriented knowledge-sharing platforms such as EU-Citizen.Science, CitSci.org, and the AfriAlliance Knowledge Hub are facilitating knowledge exchange across institutions and regions. Newly emerging citizen science practitioner networks and associations at the national, regional and global levels — especially in the Global South, including the Citizen Science Africa Association, CitizenScience.Asia and the Iberoamerican Network of Participatory Science (RICAP) — are further supporting the sharing of knowledge and skills, and nurturing collaborations across disciplines and across borders. Over the coming years, these associations will probably continue to expand to under-represented countries and regions to connect grassroots practitioners with the wider community of practice, introducing insights from unique geographical contexts and diverse stakeholder groups. This is of great importance, not only for

Table 4 | **Example limitations in citizen science and recommended solutions**

Examples of limitations	Recommendations on how to overcome them	Related design and implementation stage
Required wide range of skills outside the research subject	Establish partnerships with other project teams and stakeholders conducting similar projects and activities; work with participants who have expertise[42]	Stage 3: designing the project Stage 4: building the community
Lack of participant engagement and lack of diversity among participants	Understand participant motivations at the design stage; create tasks that appeal to different motivations; integrate tasks into the existing day-to-day activities of the participants[35]; facilitate participant feedback and exchange throughout the project[62,195,196]; avoid dependency on resources not locally available[35]; integrate co-designed processes depending on the availability of time, resources and implementation experience[62,195,196]	Stage 4: building the community
Bias related to the quality of non-professional contributions, with subsequent risk of citizen science not being recognized as a legitimate source of knowledge in decision-making	Be aware of the potential loss of power and control on the part of conventional-thinking scientists and decision-makers[24,35]	Stage 3: designing the project Stage 5: managing the data (steps related to assuring and analysing)
Bias related to human population density Temporal biases, such as the daytime and weekend bias Bias related to the extent of participant contributions Bias in the profile of participants Quality of sensors used	Examine the literature to identify potential biases and their influence on the project, and take them into account during design and analysis[56,198–204]	Stage 3: designing the project Stage 5: managing the data (steps related to assuring and analysing)
Varying data protection laws in different countries	Consider what data are essential for the project at the design stage of a project, keeping in mind, for example, the data minimization principle of the European Union General Data Protection Regulation[161]	Stage 3: designing the project Stage 5: managing the data (steps related to planning, collecting, assuring, analysing, describing and preserving)
Issues related to designing and implementing projects in remote areas	Account for potential issues while designing citizen science projects under such circumstances; ensure high level of participant engagement through co-designed approaches[205]	Stage 3: designing the project Stage 4: building the community Stage 5: managing the data (steps related to planning and collecting)
Risks related to data collection, such as loss of smartphones, visiting locations that are remote or unsafe, political risks, and so on	Clearly communicate the potential risks related to participation along with information on how to avoid them[55]	Stage 3: designing the project Stage 5: managing the data (steps related to planning and collecting)

social inclusiveness, but also in reaching out to those parts of the world where the greatest data gaps on environmental knowledge exist. Achieving this requires substantial investment in citizen science, as well as suitable guidance for establishing initiatives in such locations.

These connections, along with support for bottom-up initiatives, are of particular importance. Although we have focused on contributory citizen science projects in this Primer, often initiated by institutional scientists to crowdsource the collection or processing of data, many high-impact examples originate from grassroots initiatives that challenge established paradigms of citizen science[208]. For example, Public Lab[209] and Safecast[210] were formed by concerned citizens in response to the 2010 Deepwater Horizon oil spill and the 2011 Fukushima Daiichi nuclear disaster. Without any linkage to academic or institutional actors, both initiatives have grown into global citizen science networks empowering communities to seek environmental and social justice.

We have similarly focused in this Primer on the scientific value of citizen science approaches, but it is important to note that citizen science is also recognized as having educational value[30,38,42], environmental value[35,66] and societal value[211,212]. For initiatives with an ecological or environmental focus, six pathways have been identified through which citizen science approaches can have a positive impact on the issues examined, namely, providing insights for better environmental management, providing data evidence for policymaking, inspiring behaviour change through raised awareness and empowering social network championing, political advocacy and community action[213].

The volume and reach of these types of environmental-impact projects is likely to grow over the coming years, including those initiated by grassroots groups from the bottom up and in collaborative multi-stakeholder partnerships from the outset. As pointed out by REF.[214] in advising against a too narrow definition of citizen science, the application of citizen science approaches goes beyond developing and testing hypotheses, and includes activities related to environmental observations and complex problem solving, among others.

Some of the barriers to citizen science becoming a more mainstream research practice include low levels of

Citizen observatories
Community-based environmental monitoring initiatives that gather citizen science data for policymaking, and environmental management and governance.

awareness of the value and impact of citizen science, lack of support and recognition for career researchers in pursuing citizen science approaches, and low access to research funding[215]. Recommendations from the European community of citizen observatories to address issues of awareness, the acceptability of citizen science data and the long-term sustainability of citizen science initiatives can be summarized in five main areas. These are (i) developing effective multi-stakeholder alliances and communities of practice for knowledge exchange, (ii) building robust data value chains that are aligned with existing standards, (iii) nurturing a sustainable growth market for citizen science by addressing the data needs of local authorities and policymakers, (iv) further developing open access tools and technologies, and (v) integrating citizen science data with official data frameworks and open data systems[216].

Another powerful opportunity to mainstream citizen science approaches within research and scientific knowledge production is the global transition towards open science, which embeds public engagement with science alongside other key pillars of open science such as open access, FAIR data and open education. At the 40th session of UNESCO's General Conference in 2019, the 193 Member States unanimously adopted the Recommendation on Open Science, which contained specific proposals for improving societal access to science by increasing collaborations between scientists and societal actors, and making science more participatory, inclusive and accessible to all members of society through new ways of collaboration such as crowdfunding, crowdsourcing and scientific volunteering[28].

In 1998, the Aarhus Convention[217] was adopted, giving people in Europe the right to participate in environmental decision-making. In 2021, two new legal instruments within the Aarhus Convention were ratified to support citizen science at the national governance level: namely, the recommendations on the more effective use of electronic information tools[218], which explicitly promotes citizen science as a way to collect environmental information; and the addendum to the recommendations[219], which describes the value of citizen science and citizen observatories, and explicitly recommends the PPSR-Core set of data and metadata standards for citizen science initiatives and public participation in scientific research.

Citizen science initiatives are also providing data that inform policy and underpin decision-making at local, national, regional and global scales, for example, contributing directly to the monitoring of the United Nations Sustainable Development Goals (SDGs), where at least 33% of its 231 unique indicators can be supported through citizen science data[1]. Furthermore, citizen science data can contribute towards imminent data gaps such as 58% of the 93 environment-related SDG indicators, which do not have enough data to assess global progress[220]. Best practice examples — such as in Ghana, where citizen science data on beach litter have been integrated into the official monitoring and reporting of the relevant SDG indicator — are now emerging and illustrating the potential of citizen science for SDG reporting in developing countries[221].

Our aim within this Primer has been to provide guidance, insights and examples for designing and implementing contributory citizen science initiatives within the environmental and ecological sciences. Despite this narrow focus, we have hinted at the great wealth of examples of citizen science across all domains of research, with opportunities for participation across the full research cycle and communities initiating their own research in entirely self-led projects. We have thus highlighted only one small segment of this rapidly growing field, and we look forward to the innovations and transdisciplinary collaborations that will be introduced by researchers and project leaders in the years to come.

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1. Fraisl, D. et al. Mapping citizen science contributions to the UN sustainable development goals. *Sustain. Sci.* **15**, 1735–1751 (2020).
This is the first article to quantitatively assess the potential of citizen science for SDG indicator monitoring.
2. Haklay, M. et al. Contours of citizen science: a vignette study. *R. Soc. Open Sci.* **8**, 202108 (2021).
This article comprehensively explores the diverse perceptions of citizen science.
3. Kullenberg, C. & Kasperowski, D. What is citizen science? — A scientometric meta-analysis. *PLoS ONE* **11**, e0147152 (2016).
This article analyses the main topical focal points of citizen science.
4. Lemmens, R., Antoniou, V., Hummer, P. & Potsiou, C. in *The Science of Citizen Science* (eds. Vohland, K. et al.) 461–474 (Springer International Publishing, 2021).
5. Wynn, J. *Citizen Science In The Digital Age: Rhetoric, Science, And Public Engagement* (Univ. Alabama Press, 2017).
6. Roser, M. & Ortiz-Ospina, E. Literacy. *Our World in Data* https://ourworldindata.org/literacy (2016).
7. Pateman, R., Dyke, A. & West, S. The diversity of participants in environmental citizen science. *Citiz. Sci. Theory Pract.* **6**, 9 (2021).
8. Haklay, M. et al. in *The Science of Citizen Science* (eds Vohland, K. et al.) 13–33 (Springer International Publishing, 2021).
9. Odenwald, S. A citation study of citizen science projects in space science and astronomy. *Citiz. Sci. Theory Pract.* **3**, 5 (2018).
10. Bedessem, B., Julliard, R. & Montuschi, E. Measuring epistemic success of a biodiversity citizen science program: a citation study. *PLoS ONE* **16**, e0258350 (2021).
11. Gardiner, M. M. & Roy, H. E. The role of community science in entomology. *Annu. Rev. Entomol.* **67**, 437–456 (2022).
12. Kasperowski, D. & Hillman, T. The epistemic culture in an online citizen science project: programs, antiprograms and epistemic subjects. *Soc. Stud. Sci.* **48**, 564–588 (2018).
13. Lambers, K., Verschoof-van der Vaart, W. & Bourgeois, Q. Integrating remote sensing, machine learning, and citizen science in Dutch archaeological prospection. *Remote. Sens.* **11**, 794 (2019).
14. Froeling, F. et al. Narrative review of citizen science in environmental epidemiology: setting the stage for co-created research projects in environmental epidemiology. *Environ. Int.* **152**, 106470 (2021).
15. Hilton, N. H. Stimmen: a citizen science approach to minority language sociolinguistics. *Linguist. Vanguard.* **7**, 20190017 (2021).
16. Maisonneuve, N., Stevens, M., Niessen, M. E. & Steels, L. in *Information Technologies in Environmental Engineering* (eds Athanasiadis, I. N., Rizzoli, A. E., Mitkas, P. A. & Gómez, J. M.) 215–228 (Springer, 2009).
17. Arias, R., Capelli, L. & Diaz Jimenez, C. A new methodology based on citizen science to improve environmental odour management. *Chem. Eng. Trans.* **68**, 7–12 (2018).
18. Nascimento, S., Rubio Iglesias, J. M., Owen, R., Schade, S. & Shanley, L. in *Citizen Science — Innovation in Open Science, Society and Policy* (eds Hecker, S. et al.) 219–240 (UCL Press, 2018).
19. Den Broeder, L., Devilee, J., Van Oers, H., Schuit, A. J. & Wagemakers, A. Citizen Science for public health. *Health Promot. Int.* **33**, 505–514 (2018).
20. Bio Innovation Service. *Citizen Science For Environmental Policy: Development Of An EU Wide Inventory And Analysis Of Selected Practices* (Publications Office, 2018).
21. Mielke, J., Vermaßen, H. & Ellenbeck, S. Ideals, practices, and future prospects of stakeholder involvement in sustainability science. *Proc. Natl Acad. Sci. USA* **114**, E10648–E10657 (2017).
22. Pocock, M. J. O. et al. A vision for global biodiversity monitoring with citizen science. *Adv. Ecol. Res.* **59**, 169–223 (2018).
This article describes the opportunities of citizen science for biodiversity research.
23. Isaac, N. J. B., Strien, A. J., August, T. A., Zeeuw, M. P. & Roy, D. B. Statistics for citizen science: extracting signals of change from noisy ecological data. *Methods Ecol. Evol.* **5**, 1052–1060 (2014).
This article describes bias-correction approaches for ecological trend estimates.
24. Tengö, M., Austin, B. J., Danielsen, F. & Fernández-Llamazares, Á. Creating synergies between citizen science and Indigenous and local knowledge. *BioScience* **71**, 503–518 (2021).

25. Krick, E. Citizen experts in participatory governance: democratic and epistemic assets of service user involvement, local knowledge and citizen science. *Curr. Sociol.* https://doi.org/10.1177/00113921211059225 (2021).
26. Danielsen, F. et al. in *Citizen Science* (eds Hecker, S. et al.) 110–123 (UCL Press, 2018).
27. Luzar, J. B. et al. Large-scale environmental monitoring by Indigenous peoples. *BioScience* **61**, 771–781 (2011).
28. UNESCO. UNESCO recommendation on open science. *UNESCO* https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en (2021).
29. Wehn, U. et al. Impact assessment of citizen science: state of the art and guiding principles for a consolidated approach. *Sustain. Sci.* **16**, 1683–1699 (2021).
This article presents guidelines for a common approach in assessing citizen science impacts.
30. Aristeidou, M. & Herodotou, C. Online citizen science: a systematic review of effects on learning and scientific literacy. *Citiz. Sci. Theory Pract.* **5**, 11 (2020).
31. Peter, M., Diekötter, T. & Kremer, K. Participant outcomes of biodiversity citizen science projects: a systematic literature review. *Sustainability* **11**, 2780 (2019).
32. Turrini, T., Dörler, D., Richter, A., Heigl, F. & Bonn, A. The threefold potential of environmental citizen science — generating knowledge, creating learning opportunities and enabling civic participation. *Biol. Conserv.* **225**, 176–186 (2018).
33. ECSA. Ten principles of citizen science. *ECSA* https://zenodo.org/record/5127534 (2015).
34. Haklay, M. et al. ECSA's characteristics of citizen science. *ECSA* https://zenodo.org/record/3758668 (2020).
35. Danielsen, F. *Community-based Monitoring In The Arctic* (Univ. Alaska Press, 2020).
36. Cooper, C. B. et al. Inclusion in citizen science: the conundrum of rebranding. *Science* **372**, 1386–1388 (2021).
This article discusses issues around justice, equity, diversity and inclusion related to citizen science.
37. Eitzel, M. V. et al. Citizen science terminology matters: exploring key terms. *Citiz. Sci. Theory Pract.* **2**, 1 (2017).
This article highlights how choice of concepts and terms affects knowledge creation.
38. Bonney, R. et al. Citizen science: a developing tool for expanding science knowledge and scientific literacy. *BioScience* **59**, 977–984 (2009).
This article presents an early model for building and operating citizen science projects.
39. Haklay, M. in *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice* (eds Sui, D., Elwood, S. & Goodchild, M.) 105–122 (Springer, 2013).
40. Wiggins, A. & Crowston, K. From conservation to crowdsourcing: a typology of citizen science. In *44th Hawaii Int. Conf. on System Sciences* 1–10 (IEEE, 2011).
41. Shirk, J. L. et al. Public participation in scientific research: a framework for deliberate design. *Ecol. Soc.* **17**, art29 (2012).
This article describes multiple forms of public participation in science.
42. Tweddle, J. C., Robinson, L. D., Pocock, M. J. O. & Roy, H. E. Guide to citizen science: developing, implementing and evaluating citizen science to study biodiversity and the environment in the UK. *UK Environmental Observation Framework* https://www.ceh.ac.uk/sites/default/files/citizenscienceguide.pdf (2012).
43. Wiggins, A. et al. Data management guide for public participation in scientific research. *DataONE* https://old.dataone.org/sites/all/documents/DataONE-PPSR-DataManagementGuide.pdf (2013).
This document describes essential steps of the data management life cycle.
44. Silvertown, J., Buesching, C. D., Jacobson, S. K. & Rebelo, T. in *Key Topics in Conservation Biology* **Vol. 2** (eds Macdonald, D. W. & Willis, K. J.) 127–142 (John Wiley & Sons, 2013).
45. Pocock, M. J. O., Chapman, D. S., Sheppard, L. J. & Roy, H. E. Choosing and using citizen science: a guide to when and how to use citizen science to monitor biodiversity and the environment. *SEPA* https://www.ceh.ac.uk/sites/default/files/sepa_choosingandusingcitizenscience_interactive_4web_final_amended-blue1.pdf (2014).
46. Participatory Monitoring and Management Partnership (PMMP). Manaus Letter: recommendations for the participatory monitoring of biodiversity. *Participatory Monitoring and Management Partnership (PMMP)* https://doi.org/10.25607/OBP-965 (2015).
47. Lepczyk, C. A., Boyle, O. D., Vargo, T. L. V. & Noss, R. F. *Handbook Of Citizen Science In Ecology And Conservation* (Univ. California Press, 2020).
48. US GSA. Citizen science toolkit: basic steps for your project planning. *citizenscience.gov* https://www.citizenscience.gov/toolkit/howto/ (2022).
49. García, F. S. et al. in *The Science of Citizen Science* (eds Vohland, K. et al.) 419–437 (Springer International Publishing, 2021).
50. Van Brussel, S. & Huyse, H. Citizen science on speed? Realising the triple objective of scientific rigour, policy influence and deep citizen engagement in a large-scale citizen science project on ambient air quality in Antwerp. *J. Environ. Plan. Manag.* **62**, 534–551 (2019).
51. de Sherbinin, A. et al. The critical importance of citizen science data. *Front. Clim.* **3**, 650760 (2021).
52. Hyder, K., Townhill, B., Anderson, L. G., Delany, J. & Pinnegar, J. K. Can citizen science contribute to the evidence-base that underpins marine policy? *Mar. Policy* **59**, 112–120 (2015).
53. Wehn, U. et al. Capturing and communicating impact of citizen science for policy: a storytelling approach. *J. Environ. Manag.* **295**, 113082 (2021).
54. van Strien, A. J., van Swaay, C. A. M. & Termaat, T. Opportunistic citizen science data of animal species produce reliable estimates of distribution trends if analysed with occupancy models. *J. Appl. Ecol.* **50**, 1450–1458 (2013).
55. Laso Bayas, J. C. et al. Crowdsourcing LUCAS: citizens generating reference land cover and land use data with a mobile app. *Land* **9**, 446 (2020).
56. Cooper, C. B. Is there a weekend bias in clutch-initiation dates from citizen science? Implications for studies of avian breeding phenology. *Int. J. Biometeorol.* **58**, 1415–1419 (2014).
57. Pettibone, L. et al. *Citizen Science For All. A Guide For Citizen Science Practitioners* (Deutsches Zentrum für Integrative Biodiversitätsforschung, Helmholtz-Zentrum für Umweltforschung, Berlin-Brandenburgisches Institut für Biodiversitätsforschung, Museum für Naturkunde, Leibniz-Institut, 2016).
58. Pernat, N. et al. How media presence triggers participation in citizen science — the case of the mosquito monitoring project 'Mückenatlas'. *PLoS ONE* **17**, e0262850 (2022).
59. Crowston, K. & Prestopnik, N. R. Motivation and data quality in a citizen science game: a design science evaluation. In *46th Hawaii Int. Conf. on System Sciences* 450–459 (IEEE, 2013).
60. Funder, M., Danielsen, F., Ngaga, Y., Nielsen, M. R. & Poulsen, M. K. Reshaping conservation: the social dynamics of participatory monitoring in Tanzania's community-managed forests. *Conserv. Soc.* **11**, 218–232 (2013).
61. Deterding, S. Gamification: designing for motivation. *Interactions* **19**, 14–17 (2012).
62. West, S. & Pateman, R. Recruiting and retaining participants in citizen science: what can be learned from the volunteering literature? *Citiz. Sci. Theory Pract.* **1**, 15 (2016).
This article discusses participant motivations for engagement and volunteering.
63. Geoghegan, H., Dyke, A., Pateman, R., West, S. & Everett, G. Understanding motivations for citizen science. Final report on behalf of UKEOF. *SEI* https://www.sei.org/publications/understanding-motivations-for-citizen-science/ (2016).
64. Baruch, A., May, A. & Yu, D. The motivations, enablers and barriers for voluntary participation in an online crowdsourcing platform. *Comput. Hum. Behav.* **64**, 923–931 (2016).
65. Larson, L. R. et al. The diverse motivations of citizen scientists: does conservation emphasis grow as volunteer participation progresses? *Biol. Conserv.* **242**, 108428 (2020).
66. Danielsen, F. et al. The concept, practice, application, and results of locally based monitoring of the environment. *BioScience* **71**, 484–502 (2021).
This article summarizes the potential and intricacies of community-led citizen science.
67. Salmon, R. A., Rammell, S., Emeny, M. T. & Hartley, S. Citizens, scientists, and enablers: a tripartite model for citizen science projects. *Diversity* **13**, 309 (2021).
68. Bowser, A., Shilton, K., Preece, J. & Warrick, E. Accounting for privacy in citizen science: ethical research in a context of openness. In *Proc. 2017 ACM Conf. on Computer Supported Cooperative Work and Social Computing* 2124–2136 (ACM, 2017).
69. Ward-Fear, G., Pauly, G. B., Vendetti, J. E. & Shine, R. Authorship protocols must change to credit citizen scientists. *Trends Ecol. Evol.* **35**, 187–190 (2020).
70. Pandya, R. E. A framework for engaging diverse communities in citizen science in the US. *Front. Ecol. Environ.* **10**, 314–317 (2012).
71. Sorensen, A. E. et al. Reflecting on efforts to design an inclusive citizen science project in West Baltimore. *Citiz. Sci. Theory Pract.* **4**, 13 (2019).
72. Bonney, R., Phillips, T. B., Ballard, H. L. & Enck, J. W. Can citizen science enhance public understanding of science? *Public. Underst. Sci.* **25**, 2–16 (2016).
73. Hermoso, M. I., Martin, V. Y., Gelcich, S., Stotz, W. & Thiel, M. Exploring diversity and engagement of divers in citizen science: insights for marine management and conservation. *Mar. Policy* **124**, 104316 (2021).
74. Barahona-Segovia, R. M. et al. Combining citizen science with spatial analysis at local and biogeographical scales for the conservation of a large-size endemic invertebrate in temperate forests. *For. Ecol. Manag.* **497**, 119519 (2021).
75. Bowser, A., Wiggins, A., Shanley, L., Preece, J. & Henderson, S. Sharing data while protecting privacy in citizen science. *Interactions* **21**, 70–73 (2014).
76. Wiggins, A., Newman, G., Stevenson, R. D. & Crowston, K. Mechanisms for data quality and validation in citizen science. In *IEEE Seventh Int. Conf. on e-Science Workshops* 14–19 (IEEE, 2011).
77. Kosmala, M., Wiggins, A., Swanson, A. & Simmons, B. Assessing data quality in citizen science. *Front. Ecol. Environ.* **14**, 551–560 (2016).
This article discusses common assumptions and evidence about citizen science data quality.
78. Downs, R. R., Ramapriyan, H. K., Peng, G. & Wei, Y. Perspectives on citizen science data quality. *Front. Clim.* **3**, 615032 (2021).
This article describes perspectives on quality assessment and control issues.
79. Fritz, S. et al. Citizen science and the United Nations Sustainable Development Goals. *Nat. Sustain.* **2**, 922–930 (2019).
This article identifies the full potential of citizen science for SDG monitoring and implementation.
80. Phillips, T., Ferguson, M., Minarchek, M., Porticella, N. & Bonney, R. Evaluating learning outcomes from citizen science. *The Cornell Lab of Ornithology* https://www.birds.cornell.edu/citizenscience/wp-content/uploads/2018/10/USERS-GUIDE_linked.pdf (2014).
81. Tredick, C. A. et al. A rubric to evaluate citizen-science programs for long-term ecological monitoring. *BioScience* **67**, 834–844 (2017).
82. Kieslinger, B. et al. in *Citizen Science — Innovation in Open Science, Society and Policy* (eds Hekler, S., Haklay, M., Bowser, A., Vogel, J. & Bonn, A.) 81–95 (UCL Press, 2018).
83. Schaefer, T., Kieslinger, B., Brandt, M. & van den Bogaert, V. in *The Science of Citizen Science* (eds Vohland, K. et al.) 495–514 (Springer International Publishing, 2021).
84. Prysby, M. & Oberhauser, K. S. in *The Monarch Butterfly: Biology and Conservation* (eds Oberhauser, K. S. & Solensky, M. J.) 9–20 (Cornell Univ. Press, 2004).
85. Danielsen, F. et al. A multicountry assessment of tropical resource monitoring by local communities. *BioScience* **64**, 236–251 (2014).
The article presents the largest quantitative study to date of the accuracy of citizen science across the three tropical continents.
86. Swanson, A., Kosmala, M., Lintott, C. & Packer, C. A generalized approach for producing, quantifying, and validating citizen science data from wildlife images. *Conserv. Biol.* **30**, 520–531 (2016).
87. Serret, H., Deguines, N., Jang, Y., Lois, G. & Julliard, R. Data quality and participant engagement in citizen science: comparing two approaches for monitoring pollinators in France and South Korea. *Citiz. Sci. Theory Pract.* **4**, 22 (2019).
88. Jordan, R. C., Gray, S. A., Howe, D. V., Brooks, W. R. & Ehrenfeld, J. G. Knowledge gain and behavioral change in citizen-science programs. *Conserv. Biol. J. Soc. Conserv. Biol* **25**, 1148–1154 (2011).
89. Deguines, N., de Flores, M., Loïs, G., Julliard, R. & Fontaine, C. Fostering close encounters of

the entomological kind. *Front. Ecol. Environ.* **16**, 202–203 (2018).
90. van der Wal, R., Sharma, N., Mellish, C., Robinson, A. & Siddharthan, A. The role of automated feedback in training and retaining biological recorders for citizen science. *Conserv. Biol. J. Soc. Conserv. Biol.* **30**, 550–561 (2016).
91. Watson, D. & Floridi, L. Crowdsourced science: sociotechnical epistemology in the e-research paradigm. *Synthese* **195**, 741–764 (2018).
92. Silvertown, J. et al. Crowdsourcing the identification of organisms: a case-study of iSpot. *ZooKeys* **480**, 125–146 (2015).
93. Edgar, G. & Stuart-Smith, R. Ecological effects of marine protected areas on rocky reef communities — a continental-scale analysis. *Mar. Ecol. Prog. Ser.* **388**, 51–62 (2009).
94. Delaney, D. G., Sperling, C. D., Adams, C. S. & Leung, B. Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biol. Invasions* **10**, 117–128 (2008).
95. Johnson, N., Druckenmiller, M. L., Danielsen, F. & Pulsifer, P. L. The use of digital platforms for community-based monitoring. *BioScience* **71**, 452–466 (2021).
96. Hochmair, H. H., Scheffrahn, R. H., Basille, M. & Boone, M. Evaluating the data quality of iNaturalist termite records. *PLoS ONE* **15**, e0226534 (2020).
97. Torres, A.-C., Bedessem, B., Deguines, N. & Fontaine, C. Online data sharing with virtual social interactions favor scientific and educational successes in a biodiversity citizen science project. *J. Responsible Innov*. https://doi.org/10.1080/23299460.2021.2019970 (2022).
98. Hochachka, W. M. et al. Data-intensive science applied to broad-scale citizen science. *Trends Ecol. Evol.* **27**, 130–137 (2012).
99. Robinson, O. J., Ruiz-Gutierrez, V. & Fink, D. Correcting for bias in distribution modelling for rare species using citizen science data. *Divers. Distrib.* **24**, 460–472 (2018).
100. Johnston, A., Moran, N., Musgrove, A., Fink, D. & Baillie, S. R. Estimating species distributions from spatially biased citizen science data. *Ecol. Model.* **422**, 108927 (2020).
101. Kelling, S. et al. Can observation skills of citizen scientists be estimated using species accumulation curves? *PLoS ONE* **10**, e0139600 (2015).
102. Johnston, A., Fink, D., Hochachka, W. M. & Kelling, S. Estimates of observer expertise improve species distributions from citizen science data. *Methods Ecol. Evol.* **9**, 88–97 (2018).
103. Giraud, C., Calenge, C., Coron, C. & Julliard, R. Capitalizing on opportunistic data for monitoring relative abundances of species. *Biometrics* **72**, 649–658 (2016).
104. Fithian, W., Elith, J., Hastie, T. & Keith, D. A. Bias correction in species distribution models: pooling survey and collection data for multiple species. *Methods Ecol. Evol.* **6**, 424–438 (2015).
105. Kelling, S., Yu, J., Gerbracht, J. & Wong, W.-K. Emergent filters: automated data verification in a large-scale citizen science project. In *IEEE Seventh Int. Conf. on e-Science Workshops* 20–27 (IEEE, 2011).
106. Kelling, S. et al. Taking a ‘Big Data’ approach to data quality in a citizen science project. *Ambio* **44**, 601–611 (2015).
107. Palmer, J. R. B. et al. Citizen science provides a reliable and scalable tool to track disease-carrying mosquitoes. *Nat. Commun.* **8**, 916 (2017).
108. Callaghan, C. T., Poore, A. G. B., Hofmann, M., Roberts, C. J. & Pereira, H. M. Large-bodied birds are over-represented in unstructured citizen science data. *Sci. Rep.* **11**, 19073 (2021).
109. Brashares, J. S. & Sam, M. K. How much is enough? Estimating the minimum sampling required for effective monitoring of African reserves. *Biodivers. Conserv.* **14**, 2709–2722 (2005).
110. Andrianandrasana, H. T., Randriamahefasoa, J., Durbin, J., Lewis, R. E. & Ratsimbazafy, J. H. Participatory ecological monitoring of the Alaotra Wetlands in Madagascar. *Biodivers. Conserv.* **14**, 2757–2774 (2005).
111. Jiguet, F., Devictor, V., Julliard, R. & Couvet, D. French citizens monitoring ordinary birds provide tools for conservation and ecological sciences. *Acta Oecologica* **44**, 58–66 (2012).
112. Martin, G., Devictor, V., Motard, E., Machon, N. & Porcher, E. Short-term climate-induced change in French plant communities. *Biol. Lett.* **15**, 20190280 (2019).
113. Guillera-Arroita, G. Modelling of species distributions, range dynamics and communities under imperfect detection: advances, challenges and opportunities. *Ecography* **40**, 281–295 (2017).
114. Gregory, R. D. et al. Developing indicators for European birds. *Phil. Trans. R. Soc. B* **360**, 269–288 (2005).
115. Cima, V. et al. A test of six simple indices to display the phenology of butterflies using a large multi-source database. *Ecol. Indic.* **110**, 105885 (2020).
116. Weisshaupt, N., Lehikoinen, A., Mäkinen, T. & Koistinen, J. Challenges and benefits of using unstructured citizen science data to estimate seasonal timing of bird migration across large scales. *PLoS ONE* **16**, e0246572 (2021).
117. Isaac, N. J. B. et al. Data integration for large-scale models of species distributions. *Trends Ecol. Evol.* **35**, 56–67 (2020).
118. Deguines, N., Julliard, R., de Flores, M. & Fontaine, C. Functional homogenization of flower visitor communities with urbanization. *Ecol. Evol.* **6**, 1967–1976 (2016).
119. Desaegher, J., Nadot, S., Fontaine, C. & Colas, B. Floral morphology as the main driver of flower-feeding insect occurrences in the Paris region. *Urban. Ecosyst.* **21**, 585–598 (2018).
120. Osenga, E. C., Vano, J. A. & Arnott, J. C. A community-supported weather and soil moisture monitoring database of the Roaring Fork catchment of the Colorado River Headwaters. *Hydrol. Process.* **35**, e14081 (2021).
121. Ryan, S. F. et al. The role of citizen science in addressing grand challenges in food and agriculture research. *Proc. R. Soc. B* **285**, 20181977 (2018).
122. Paap, T., Wingfield, M. J., Burgess, T. I., Hulbert, J. M. & Santini, A. Harmonising the fields of invasion science and forest pathology. *NeoBiota* **62**, 301–332 (2020).
123. Newman, G. et al. The future of citizen science: emerging technologies and shifting paradigms. *Front. Ecol. Environ.* **10**, 298–304 (2012).
This article gives a history account of the development of citizen science.
124. Clark, G. F. et al. A visualization tool for citizen-science marine debris big data. *Water Int.* **46**, 211–223 (2021).
125. Gray, A., Robertson, C. & Feick, R. CWDAT — an open-source tool for the visualization and analysis of community-generated water quality data. *ISPRS Int. J. Geo-Inf.* **10**, 207 (2021).
126. Hoyer, T., Moritz, J. & Moser, J. Visualization and perception of data gaps in the context of citizen science projects. *KN J. Cartogr. Geogr. Inf.* **71**, 155–172 (2021).
127. Liu, H.-Y., Dörler, D., Heigl, F. & Grossberndt, S. in *The Science of Citizen Science* (eds Vohland, K. et al.) 439–459 (Springer International Publishing, 2021).
128. Miller-Rushing, A., Primack, R. & Bonney, R. The history of public participation in ecological research. *Front. Ecol. Environ.* **10**, 285–290 (2012).
129. Kobori, H. et al. Citizen science: a new approach to advance ecology, education, and conservation. *Ecol. Res.* **31**, 1–19 (2016).
130. Clavero, M. & Revilla, E. Mine centuries-old citizen science. *Nature* **510**, 35–35 (2014).
131. Kalle, R., Pieroni, A., Svanberg, I. & Sõukand, R. Early citizen science action in ethnobotany: the case of the folk medicine collection of Dr. Mihkel Ostrov in the territory of present-day Estonia, 1891–1893. *Plants* **11**, 274 (2022).
132. Chandler, M. et al. Contribution of citizen science towards international biodiversity monitoring. *Biol. Conserv.* **213**, 280–294 (2017).
This article highlights the magnitude of citizen science contributions to global biodiversity datasets.
133. Groom, Q., Weatherdon, L. & Geijzendorffer, I. R. Is citizen science an open science in the case of biodiversity observations? *J. Appl. Ecol.* **54**, 612–617 (2017).
134. Cooper, C. B., Shirk, J. & Zuckerberg, B. The invisible prevalence of citizen science in global research: migratory birds and climate change. *PLoS ONE* **9**, e106508 (2014).
135. Morales, C. L. et al. Does climate change influence the current and future projected distribution of an endangered species? The case of the southernmost bumblebee in the world. *J. Insect Conserv.* **26**, 257–269 (2022).
136. Campbell, H. & Engelbrecht, I. The Baboon Spider Atlas — using citizen science and the ‘fear factor’ to map baboon spider (Araneae: Theraphosidae) diversity and distributions in southern Africa. *Insect Conserv. Divers.* **11**, 143–151 (2018).
137. Callaghan, C. T. et al. Three frontiers for the future of biodiversity research using citizen science data. *BioScience* **71**, 55–63 (2021).
138. Croft, S., Chauvenet, A. L. M. & Smith, G. C. A systematic approach to estimate the distribution and total abundance of British mammals. *PLoS ONE* **12**, e0176339 (2017).
139. Hsing, P. et al. Economical crowdsourcing for camera trap image classification. *Remote Sens. Ecol. Conserv.* **4**, 361–374 (2018).
140. Altwegg, R. & Nichols, J. D. Occupancy models for citizen-science data. *Methods Ecol. Evol.* **10**, 8–21 (2019).
141. Green, S. E., Rees, J. P., Stephens, P. A., Hill, R. A. & Giordano, A. J. Innovations in camera trapping technology and approaches: the integration of citizen science and artificial intelligence. *Animals* **10**, 132 (2020).
142. Hsing, P.-Y. et al. Citizen scientists: school students conducting, contributing to and communicating ecological research — experiences of a school–university partnership. *Sch. Sci. Rev.* **101**, 67–74 (2020).
143. Degnan, L. MammalWeb citizen science wildlife monitoring. *Vimeo* https://vimeo.com/237565215 (2017).
144. Hsing, P.-Y. et al. Large-scale mammal monitoring: the potential of a citizen science camera-trapping project in the UK. *Ecol. Solut. Evid*. (in the press).
145. Chapman, H. Spotting wildlife helps teens cope with life in lockdown. *The Northern Echo* https://www.thenorthernecho.co.uk/news/18459359.spotting-wildlife-helps-teens-cope-life-lockdown/ (2020).
146. McKie, R. How an army of ‘citizen scientists’ is helping save our most elusive animals. *The Guardian* https://www.theguardian.com/environment/2019/jul/28/britain-elusive-animals-fall-into-camera-trap-citizen-scientist (2019).
147. Deguines, N., Julliard, R., de Flores, M. & Fontaine, C. The whereabouts of flower visitors: contrasting land-use preferences revealed by a country-wide survey based on citizen science. *PLoS ONE* **7**, e45822 (2012).
148. Levé, M., Baudry, E. & Bessa-Gomes, C. Domestic gardens as favorable pollinator habitats in impervious landscapes. *Sci. Total Environ.* **647**, 420–430 (2019).
149. Aparicio Camín, N., Comaposada, A., Paul, E., Maceda-Veiga, A. & Piera, J. Analysis of species richness in Barcelona beaches using a citizen science based approach (Sociedad Ibérica de Ecología, 2019).
150. Chao, A., Colwell, R. K., Chiu, C. & Townsend, D. Seen once or more than once: applying Good–Turing theory to estimate species richness using only unique observations and a species list. *Methods Ecol. Evol.* **8**, 1221–1232 (2017).
151. Mominó, J. M., Piera, J. & Jurado, E. in *Analyzing the Role of Citizen Science in Modern Research* (eds Ceccaroni, L. & Piera, J.) 231–245 (IGI Global, 2017).
152. Salvador, X. et al. *Guia Participativa Marina del Barcelonès* (Marcombo, 2021).
153. Carayannis, E. G., Barth, T. D. & Campbell, D. F. The Quintuple Helix innovation model: global warming as a challenge and driver for innovation. *J. Innov. Entrep.* **1**, 2 (2012).
154. Goodchild, M. F. Citizens as sensors: the world of volunteered geography. *GeoJournal* **69**, 211–221 (2007).
155. Capineri, C. et al. *European Handbook of Crowdsourced Geographic Information* (Ubiquity Press, 2016).
156. Skarlatidou, A. & Haklay, M. *Geographic Citizen Science Design: No One Left Behind* (UCL Press, 2021).
157. Haklay, M. & Weber, P. OpenStreetMap: user-generated street maps. *IEEE Pervasive Comput.* **7**, 12–18 (2008).
158. Jeddi, Z. et al. Citizen seismology in the Arctic. *Front. Earth Sci*. https://doi.org/10.3389/feart.2020.00139 (2020).
159. Eurostat. LUCAS — Land use and land cover survey. *eurostat* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=LUCAS_-_Land_use_and_land_cover_survey (2021).
160. Laso Bayas, J. et al. Crowdsourcing in-situ data on land cover and land use using gamification and mobile technology. *Remote. Sens.* **8**, 905 (2016).

161. EU. Regulation (EU) 2016/679 Of The European Parliament And Of The Council, Article 5(c). *EU* https://eur-lex.europa.eu/eli/reg/2016/679/oj (2016).
162. Danielsen, F. et al. Community monitoring for REDD+: international promises and field realities. *Ecol. Soc.* **18**, 41 (2013).
163. Boissière, M., Herold, M., Atmadja, S. & Sheil, D. The feasibility of local participation in measuring, reporting and verification (PMRV) for REDD. *PLoS ONE* **12**, e0176897 (2017).
164. Walker, D. W., Smigaj, M. & Tani, M. The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. *WIREs Water* **8**, e1488 (2021).
165. Danielsen, F. et al. Community monitoring of natural resource systems and the environment. *Annu. Rev. Environ. Resour*. https://doi.org/10.1146/annurev-environ-012220-022325 (2022).
166. Pecl, G. T. et al. Redmap Australia: challenges and successes with a large-scale citizen science-based approach to ecological monitoring and community engagement on climate change. *Front. Mar. Sci*. https://doi.org/10.3389/fmars.2019.00349 (2019).
167. Shinbrot, X. A. et al. Quiahua, the first citizen science rainfall monitoring network in Mexico: filling critical gaps in rainfall data for evaluating a payment for hydrologic services program. *Citiz. Sci. Theory Pract.* **5**, 19 (2020).
168. Little, K. E., Hayashi, M. & Liang, S. Community-based groundwater monitoring network using a citizen-science approach. *Groundwater* **54**, 317–324 (2016).
169. Wolff, E. The promise of a "people-centred" approach to floods: types of participation in the global literature of citizen science and community-based flood risk reduction in the context of the Sendai Framework. *Prog. Disaster Sci.* **10**, 100171 (2021).
170. Hauser, D. D. W. et al. Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. *Environ. Res. Lett.* **16**, 095003 (2021).
171. Soroye, P., Ahmed, N. & Kerr, J. T. Opportunistic citizen science data transform understanding of species distributions, phenology, and diversity gradients for global change research. *Glob. Change Biol.* **24**, 5281–5291 (2018).
172. Robles, M. C. et al. Clouds around the world: how a simple citizen science data challenge became a worldwide success. *Bull. Am. Meteorol. Soc.* **101**, E1201–E1213 (2020).
173. Beeden, R. J. et al. Rapid survey protocol that provides dynamic information on reef condition to managers of the Great Barrier Reef. *Environ. Monit. Assess.* **186**, 8527–8540 (2014).
174. Miller-Rushing, A. J., Gallinat, A. S. & Primack, R. B. Creative citizen science illuminates complex ecological responses to climate change. *Proc. Natl Acad. Sci. USA* **116**, 720–722 (2019).
175. Kress, W. J. et al. Citizen science and climate change: mapping the range expansions of native and exotic plants with the mobile app Leafsnap. *BioScience* **68**, 348–358 (2018).
176. Kirchhoff, C. et al. Rapidly mapping fire effects on biodiversity at a large-scale using citizen science. *Sci. Total Environ.* **755**, 142348 (2021).
177. Wang, T., Hamann, A., Spittlehouse, D. & Carroll, C. Locally downscaled and spatially customizable climate data for historical and future periods for North America. *PLoS ONE* **11**, e0156720 (2016).
178. Soil Survey Staff, Natural Resources Conservation Service & USDA. Web soil survey. *USDA* https://websoilsurvey.nrcs.usda.gov/ (2019).
179. Cooper, C. B., Hochachka, W. M. & Dhondt, A. A. in *Citizen Science* (eds Dickinson, J. L. & Bonney, R.) 99–113 (Cornell Univ. Press, 2012).
180. Bastin, L., Schade, S. & Schill, C. in *Mapping and the Citizen Sensor* (eds Foody, G. et al.) 249–272 (Ubiquity Press, 2017).
181. Resnik, D. B., Elliott, K. C. & Miller, A. K. A framework for addressing ethical issues in citizen science. *Environ. Sci. Policy* **54**, 475–481 (2015).
This article outlines basic considerations for ethical research practices in citizen science.
182. Brashares, J. S., Arcese, P. & Sam, M. K. Human demography and reserve size predict wildlife extinction in West Africa. *Proc. R. Soc. Lond. B* **268**, 2473–2478 (2001).
183. Lotfian, M., Ingensand, J. & Brovelli, M. A. The partnership of citizen science and machine learning: benefits, risks, and future challenges for engagement, data collection, and data quality. *Sustainability* **13**, 8087 (2021).
184. Kissling, W. D. et al. Towards global interoperability for supporting biodiversity research on essential biodiversity variables (EBVs). *Biodiversity* **16**, 99–107 (2015).
185. Wilkinson, M. D. et al. The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* **3**, 160018 (2016).
186. Carroll, S. R., Herczog, E., Hudson, M., Russell, K. & Stall, S. Operationalizing the CARE and FAIR principles for Indigenous data futures. *Sci. Data* **8**, 108 (2021).
187. UKEOF Citizen Science Working. Data management planning for citizen science. *Ocean Best Practices* https://repository.oceanbestpractices.org/handle/11329/1406 (2020).
This document provides advice about the development of data management plans.
188. Hansen, J. S. et al. Research data management challenges in citizen science projects and recommendations for library support services. A scoping review and case study. *Data Sci. J.* **20**, 25 (2021).
189. Croucher, M., Graham, L., James, T., Krystalli, A. & Michonneau, F. A guide to reproducible code. *British Ecological Society* https://www.britishecologicalsociety.org/publications/guides-to/ (2019).
190. Parker, A., Dosemagen, S., Molloy, J., Bowser, A. & Novak, A. Open hardware: an opportunity to build better science. *Wilson Center* https://www.wilsoncenter.org/publication/open-hardware-opportunity-build-better-science (2021).
191. Palmer, M. S., Dewey, J. & Huebner, S. Snapshot Safari educational materials. *Libraries Digital Conservancy* https://hdl.handle.net/11299/217102 (2020).
192. Campbell, J., Bowser, A., Fraisl, D. & Meloche, M. in *Data for Good Exchange* (IIASA, 2019).
193. Fraisl, D. et al. Demonstrating the potential of Picture Pile as a citizen science tool for SDG monitoring. *Environ. Sci. Policy* **128**, 81–93 (2022).
194. Humm, C. & Schrögel, P. Science for all? Practical recommendations on reaching underserved audiences. *Front. Commun.* https://doi.org/10.3389/fcomm.2020.00042 (2020).
195. Clary, E. G. & Snyder, M. The motivations to volunteer: theoretical and practical considerations. *Curr. Dir. Psychol. Sci.* **8**, 156–159 (1999).
196. Hobbs, S. J. & White, P. C. L. Motivations and barriers in relation to community participation in biodiversity recording. *J. Nat. Conserv.* **20**, 364–373 (2012).
197. Lukyanenko, R., Wiggins, A. & Rosser, H. K. Citizen science: an information quality research frontier. *Inf. Syst. Front.* **22**, 961–983 (2020).
198. Mair, L. & Ruete, A. Explaining spatial variation in the recording effort of citizen science data across multiple taxa. *PLoS ONE* **11**, e0147796 (2016).
199. Petrovan, S. O., Vale, C. G. & Sillero, N. Using citizen science in road surveys for large-scale amphibian monitoring: are biased data representative for species distribution? *Biodivers. Conserv.* **29**, 1767–1781 (2020).
200. Courter, J. R., Johnson, R. J., Stuyck, C. M., Lang, B. A. & Kaiser, E. W. Weekend bias in Citizen Science data reporting: implications for phenology studies. *Int. J. Biometeorol.* **57**, 715–720 (2013).
201. Cretois, B. et al. Identifying and correcting spatial bias in opportunistic citizen science data for wild ungulates in Norway. *Ecol. Evol.* **11**, 15191–15204 (2021).
202. Haklay, M. E. in *European Handbook of Crowdsourced Geographic Information* (eds Capineri, C. et al.) 35–44 (Ubiquity Press, 2016).
203. Haklay, M. in *Citizen Science* (eds Haklay, M. et al.) 52–62 (UCL Press, 2018).
204. Schade, S., Herding, W., Fellermann, A. & Kotsev, A. Joint statement on new opportunities for air quality sensing — lower-cost sensors for public authorities and citizen science initiatives. *Res. Ideas Outcomes* **5**, e34059 (2019).
205. Moustard, F. et al. Using Sapelli in the field: methods and data for an inclusive citizen science. *Front. Ecol. Evol* https://doi.org/10.3389/fevo.2021.638870 (2021).
206. Pettibone, L. et al. Transdisciplinary sustainability research and citizen science: options for mutual learning. *GAIA — Ecol. Perspect. Sci. Soc.* **27**, 222–225 (2018).
207. Low, R., Schwerin, T. & Codsi, R. *Citizen Science As A Tool For Transdisciplinary Research And Stakeholder Engagement* (ESSOAr, 2020).
208. Ottinger, G. in *The Routledge Handbook of the Political Economy of Science* (eds Tyfield, D., Lave, R., Randalls, S. & Thorpe, C.) 351–364 (Routledge, 2017).
209. Rey-Mazón, P., Keysar, H., Dosemagen, S., D'Ignazio, C. & Blair, D. Public lab: community-based approaches to urban and environmental health and justice. *Sci. Eng. Ethics* **24**, 971–997 (2018).
210. Brown, A., Franken, P., Bonner, S., Dolezal, N. & Moross, J. Safecast: successful citizen-science for radiation measurement and communication after Fukushima. *J. Radiol. Prot.* **36**, S82–S101 (2016).
211. Pocock, M. J. O. et al. Developing the global potential of citizen science: assessing opportunities that benefit people, society and the environment in East Africa. *J. Appl. Ecol.* **56**, 274–281 (2019).
212. Gollan, J., de Bruyn, L. L., Reid, N. & Wilkie, L. Can volunteers collect data that are comparable to professional scientists? A study of variables used in monitoring the outcomes of ecosystem rehabilitation. *Environ. Manag.* **50**, 969–978 (2012).
213. van Noordwijk, T. C. G. E. et al. in *The Science of Citizen Science* (eds Vohland, K. et al.) 373–395 (Springer International Publishing, 2021).
214. Auerbach, J. et al. The problem with delineating narrow criteria for citizen science. *Proc. Natl. Acad. Sci. USA* **116**, 15336–15337 (2019).
215. Gold, M., Wehn, U., Bilbao, A. & Hager, G. EU Citizen observatories landscape report II: addressing the challenges of awareness, acceptability, and sustainability. *EU* https://zenodo.org/record/4472670 (2020).
216. WeObserve Consortium. Roadmap for the uptake of the citizen observatories' knowledge base. *WeObserve Consortium* https://zenodo.org/record/4646774 (2021).
217. UNECE. Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention). *UNECE* https://unece.org/fileadmin/DAM/env/pp/documents/cep43e.pdf (1998).
218. UNECE. Draft updated recommendations on the more effective use of electronic information tools. *UNECE* https://unece.org/sites/default/files/2021-08/ECE_MP.PP_2021_20_E.pdf (2021).
219. UNECE. Draft updated recommendations on the more effective use of electronic information tools, Addendum. *UNECE* https://unece.org/sites/default/files/2021-08/ECE_MP.PP_2021_20_Add.1_E.pdf (2021).
220. UNEP. Measuring progress: environment and the SDGs. *UNEP* http://www.unep.org/resources/publication/measuring-progress-environment-and-sdgs (2021).
221. SDSN TReNDS. Strengthening measurement of marine litter in Ghana. How citizen science is helping to measure progress on SDG 14.1.1b. *SDSN TReNDS* https://storymaps.arcgis.com/stories/2622af0a0c7d4c709c3d09f4cc249f7d (2021).
222. Goudeseune, L. et al. Citizen science toolkit for biodiversity scientists. *biodiversa* https://zenodo.org/record/3979343 (2020).
223. Veeckman, C., Talboom, S., Gijsel, L., Devoghel, H. & Duerinckx, A. Communication in citizen science. A practical guide to communication and engagement in citizen science. *SCivil* https://www.scivil.be/sites/default/files/paragraph/files/2020-01/Scivil%20Communication%20Guide.pdf (2019).
224. Durham, E., Baker, S., Smith, M., Moore, E. & Morgan, V. BiodivERsA: stakeholder engagement handbook. *biodiversa* https://www.biodiversa.org/702 (2014).
225. WeObserve Consortium. WeObserve Cookbook. *WeObserve Consortium* https://zenodo.org/record/5493543 (2021).
226. Danielsen, F. et al. Testing focus groups as a tool for connecting Indigenous and local knowledge on abundance of natural resources with science-based land management systems. *Conserv. Lett.* **7**, 380–389 (2014).
227. Elliott, K. C., McCright, A. M., Allen, S. & Dietz, T. Values in environmental research: citizens' views of scientists who acknowledge values. *PLoS ONE* **12**, e0186049 (2017).
228. Yamamoto, Y. T. Values, objectivity and credibility of scientists in a contentious natural resource debate. *Public. Underst. Sci.* **21**, 101–125 (2012).

229. Danielsen, F. et al. in *Handbook of Citizen Science in Ecology and Conservation* (eds Lepczyk, C. A., Boyle, O. D., Vargo, T. L. V. & Noss, R. F.) 25–29 (Univ. California Press, 2020).
230. Eicken, H. et al. Connecting top-down and bottom-up approaches in environmental observing. *BioScience* **71**, 467–483 (2021).
This article highlights the benefits of linking community- and science/policy-led approaches.
231. Slough, T. et al. Adoption of community monitoring improves common pool resource management across contexts. *Proc. Natl Acad. Sci. USA* **118**, e2015367118 (2021).
232. Wilderman, C. C., Barron, A. & Imgrund, L. Top down or bottom up? ALLARM's experience with two operational models for community science. In *4th Natl Monitoring Conf*. (National Water Quality Monitoring Council, 2004).
233. Johnson, N. et al. Community-based monitoring and Indigenous knowledge in a changing Arctic: a review for the sustaining Arctic Observing Networks. *Ocean Best Practices* https://repository.oceanbestpractices.org/handle/11329/1314 (2016).
234. Lau, J. D., Gurney, G. G. & Cinner, J. Environmental justice in coastal systems: perspectives from communities confronting change. *Glob. Environ. Change* **66**, 102208 (2021).
235. Lyver, P. O. B. et al. An Indigenous community-based monitoring system for assessing forest health in New Zealand. *Biodivers. Conserv.* **26**, 3183–3212 (2017).
236. Cuyler, C. et al. Using local ecological knowledge as evidence to guide management: a community-led harvest calculator for muskoxen in Greenland. *Conserv. Sci. Pract.* **2**, e159 (2020).
237. Fox, J. A. Social accountability: what does the evidence really say? *World Dev.* **72**, 346–361 (2015).
238. Wheeler, H. C. et al. The need for transformative changes in the use of Indigenous knowledge along with science for environmental decision-making in the Arctic. *People Nat.* **2**, 544–556 (2020).
239. Storey, R. G., Wright-Stow, A., Kin, E., Davies-Colley, R. J. & Stott, R. Volunteer stream monitoring: do the data quality and monitoring experience support increased community involvement in freshwater decision making? *Ecol. Soc.* **21**, art32 (2016).
240. Brofeldt, S. et al. Community-based monitoring of tropical forest crimes and forest resources using information and communication technology — experiences from Prey Lang, Cambodia. *Citiz. Sci. Theory Pract.* **3**, 4 (2018).
241. Menton, M. & Le Billon, P. *Environmental Defenders: Deadly Struggles For Life And Territory* (Routledge, 2021).
242. Eastman, L. B., Hidalgo-Ruz, V., Macaya-Caquilpán, V., Nũñez, P. & Thiel, M. The potential for young citizen scientist projects: a case study of Chilean schoolchildren collecting data on marine litter. *J. Integr. Coast. Zone Manag.* **14**, 569–579 (2014).
243. Hidalgo-Ruz, V. & Thiel, M. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. *Mar. Environ. Res.* **87–88**, 12–18 (2013).
244. Kruse, K., Kiessling, T., Knickmeier, K., Thiel, M. & Parchmann, I. in *Engaging Learners with Chemistry* (eds Ilka P., Shirley S. & Jan A.) 225–240 (Royal Society of Chemistry, 2020).
245. Wichman, C. S. et al. Promoting pro-environmental behavior through citizen science? A case study with Chilean schoolchildren on marine plastic pollution. *Mar. Policy* **141**, 105035 (2022).
246. Bravo, M. et al. Anthropogenic debris on beaches in the SE Pacific (Chile): results from a national survey supported by volunteers. *Mar. Pollut. Bull.* **58**, 1718–1726 (2009).
247. Hidalgo-Ruz, V. et al. Spatio-temporal variation of anthropogenic marine debris on Chilean beaches. *Mar. Pollut. Bull.* **126**, 516–524 (2018).
248. Honorato-Zimmer, D. et al. Mountain streams flushing litter to the sea — Andean rivers as conduits for plastic pollution. *Environ. Pollut.* **291**, 118166 (2021).
249. Amenábar Cristi, M. et al. The rise and demise of plastic shopping bags in Chile — broad and informal coalition supporting ban as a first step to reduce single-use plastics. *Ocean. Coast. Manag.* **187**, 105079 (2020).
250. Kiessling, T. et al. Plastic Pirates sample litter at rivers in Germany — riverside litter and litter sources estimated by schoolchildren. *Environ. Pollut.* **245**, 545–557 (2019).
251. Kiessling, T. et al. Schoolchildren discover hotspots of floating plastic litter in rivers using a large-scale collaborative approach. *Sci. Total. Environ.* **789**, 147849 (2021).

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Author contributions

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Forest Health Watch program: https://foresthealth.org/
FotoQuest Go: http://fotoquest-go.org/
Global Earth Challenge Marine Litter Data Integration Platform: https://globalearthchallenge.earthday.org/datasets/data-earth-challenge-integrated-data-plastic-pollution-mlw-mdmap-icc-2015-2018/explore?location=2.132530%2C2.357206%2C1.89
Great Southern BioBlitz: https://www.inaturalist.org/projects/great-southern-bioblitz-2021-umbrella
iNaturalist: https://github.com/inaturalist/
Iberoamerican Network of Participatory Science (RICAP): http://cienciaparticipativa.net/la-ricap/
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National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Monitoring and Assessment Project's Accumulation Data: https://mdmap.orr.noaa.gov/
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