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Citizen science in environmental and ecological sciences

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Abstract

Citizen science, the public participation in scientific research and knowledge production, is an increasingly acknowledged approach applied in a wide range of scientific domains, and particularly within the environmental and ecological sciences. We introduce contributory citizen science as a method to scientists and practitioners in this domain focusing on the full life cycle of the 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. Aspects of reproducibility and data sharing are considered from placing citizen science within an encompassing open science perspective. Finally, we discuss limitations and challenges for future research and present an outlook for future paths of citizen science across multiple science domains.

1 Introduction

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 new discoveries, such as in astrophysics[12] and archaeology projects[13]; new insights, such as in epidemiology[14] and socio-linguistics projects[15]; evidence-based policy making, 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 fills important data gaps across both time and space[23] that might not otherwise be possible without the contribution of many PARTICIPANTS, including the participation of 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 that encourages scientific collaborations that benefit both science and society, and opens 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 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 across the globe including regional networks, such as the European Citizen Science Association or the Iberoamerican Network of Participatory Science (RICAP), and globally via the Global Citizen Science Partnership. Some of the key principles that underlie good practice have been encapsulated by an international community of practitioners in “The Ten Principles of Citizen Science”[33]. The different factors that make up the unique aspects are described in “ECSA’s Characteristics of Citizen Science”[34].

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 paper. 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 within 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 environmental and ecological sciences because it can provide a manageable entry point into citizen science practices, has a wealth of examples to draw on, and thus allows 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 for the Primer to serve as a useful review and general resource for those who are experienced in the field.

2 Experimentation

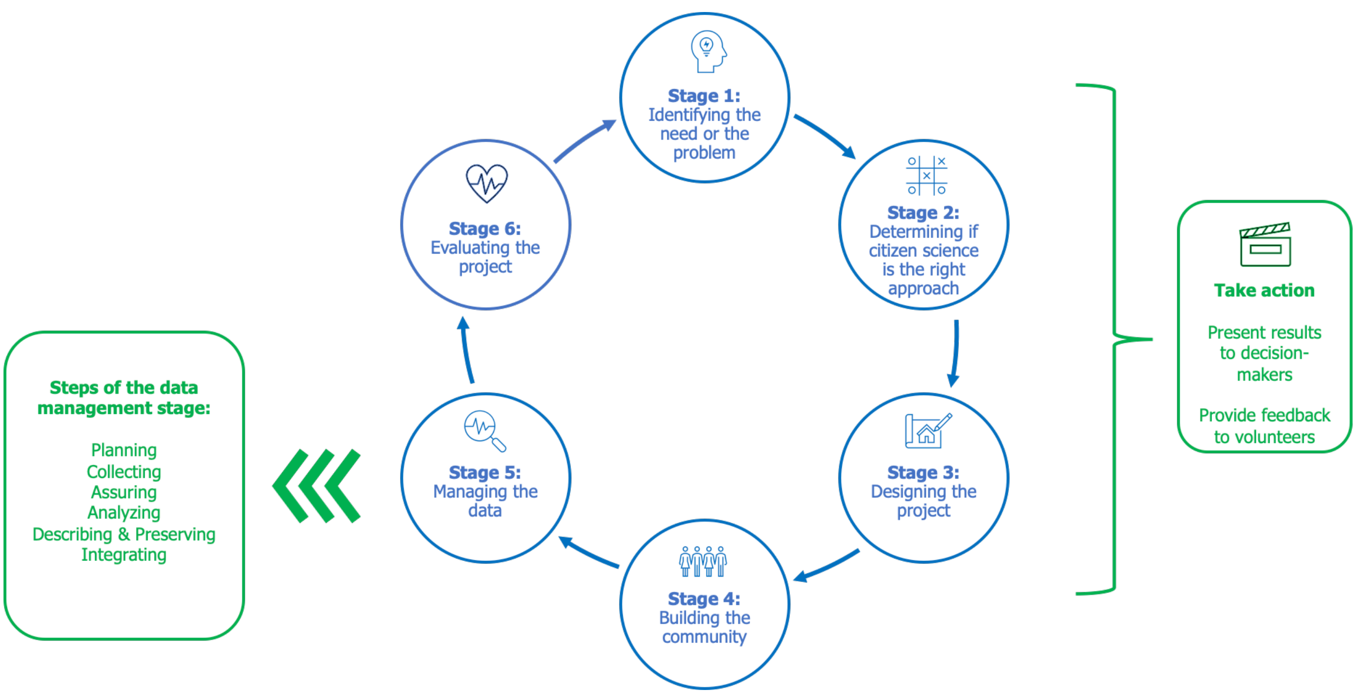
In this section, we provide an overview of different design and implementation stages of contributory citizen science projects in the field of ecology and environmental sciences, some of which will be described in more detail in subsequent sections. Various guidelines exist for designing and implementing 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. Note that each of the stages presented in this section are interconnected and one step does not necessarily need to end for the other 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 these stages need to be adapted to the context of the project.

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[221]	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 if citizen science is the right approach
Communication in Citizen Science[222]	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 programs, 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 lifecycle 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 a 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 programs	All stages
Manaus Letter: Recommendations for the Participatory Monitoring of Biodiversity[46]	Guiding organizers of citizen science programs about 'good practice' in participatory monitoring of biodiversity and natural resource use	All stages
Stakeholder Engagement Handbook[223]	Offering practical guidance to researchers to better plan and engage with non-academic stakeholders, including policy makers	Stage 4: Building the Community
WeObserve Cookbook[224]	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. Data Management Stage (Stage 5) highlighted in green box (bottom left). Project teams should be action oriented while designing and implementing citizen science initiatives, as presented in green box (right).

Stage 1: Identifying the need or the problem

As with any project, problem scoping is the first stage of the citizen science project lifecycle, where 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], as mentioned in the introduction section.

At this stage, it is useful to think about the key stakeholders and to try to understand the problem from their perspective, especially those from target groups. Possible solutions to the problem and their limitations need to be considered, and based on that, research questions and general objectives should be formulated. Acknowledging, as is sometimes the case in ecological and environmental studies, that stakeholders may not have a specific problem or research question identified, but instead 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 methods available that could be useful for the project. Within the rapidly growing citizen science field and literature, it is likely to identify similar problems and needs that were 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: Determining if citizen science is the right approach

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 in addressing the problem or need and the research questions identified in the first stage[45]. The goal is to understand if involving citizen science participants will help achieve the desired results, while at the same time benefitting them by addressing their needs 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 if 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 another key consideration, and it is important to review the available resources and requirements for delivering on project objectives prior to starting[42]. This includes considerations related to human resources including the skills that are needed in the team and tasks and responsibilities of the project staff. Equipment, travel, or training necessary for data collection should also be regarded.

Examples of projects that are suitable for citizen science approaches are observations of the natural environment including wildlife and species, detecting change 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 demand a great deal of time commitment such as collecting detailed measurements every few hours or every day over a season[45].

Stage 3: Designing the project

In the design stage, 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 for answering 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, behavioral change, or raised interest in science and community building, which should also be determined[1,2,52,53]. Defining the project objectives in detail will help identify the data needs and data collection tools and formats, which can 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 if similar data collection formats and methods are available and if re-use of existing data collection platforms is possible. TABLE 2 provides some examples of existing citizen science platforms for re-use. Where and how to store the data and for how long, and how to share them also need to be considered in the design stage. These aspects are discussed in more detail in the reproducibility and data deposition section below.

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://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://www.inaturalist.org/
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 analyzing 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

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 avoid or reduce the impact of such problems[54,55]. Explicitly communicating the potential sampling biases to the audience will help improve data quality and can increasing 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, a project website, and forum are some examples of commonly used means of communication[48,57]. Furthermore, establishing partnerships with mass media such as newspapers, TV channels or radio stations has shown to be a successful strategy to increase 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 are continually assessed to allow for diversity and inclusion.

Stage 4: Building the Community

The next stage is developing a community building plan for the project. For successful community building, knowing the community and understanding what could motivate them to contribute time and skills for the project is important. Identifying the age groups, education levels and interests of the community members, among others, help in getting to know the community[48]. Motivation for participation can vary between community members and may include helping science and 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 project type 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 relationship between all people involved creating 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 due 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-author in scientific publications or providing a visualization tool on the project website that shows participant contributions, which would require key considerations on 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 participation of people with diverse backgrounds, ethnicities, income and education levels, and with varying access to and use of technology, among others[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 geographic coverage and representativity as well as to address a broader range of stakeholder

Stage 5: Managing the Data

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]. Note that the steps related to (i) Planning, (ii) Collecting and (iii) Assuring are presented in this section, while (iv) Analyzing, (v) Describing and Preserving, and (vi) 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 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 document them in 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, identify associated costs and 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, sound, observations, water samples, sensor data, such as temperature and noise or humans as sensors such as odor, 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 based on the 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 them 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

This step refers to the type of information needed to achieve the objectives of the project. This could be project related information, such as observations on 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 while 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, because 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 generate the required data.

Assuring

This step is about 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, while providing training to participants or developing standard protocols for data collection are part of QA, 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 the reuse opportunities[78,79].

Stage 6: Evaluating the Project

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 that is conducted during implementation and summative evaluation that is implemented usually 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, which allows improvement at any stage. In some cases, evaluation can be a funder requirement, along with identifying the short- and long-term impacts of the project. Agreeing on metrics for measuring success, and 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].

3 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. Furthermore, we provide examples of tools and methods to support data analysis in citizen science.

Training and testing participants constitutes one approach 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 a training to provide higher quality contributions[55,88,89]. Additionally, training can occur through community consensus of data, where data are cross-checked and validated by other participants[90].

Another approach to improve data quality involves testing participant's 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 assess data accuracy and support the project team to filter or weight the data based on 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, which is using multiple observers, methods, and data sources to improve quality and overcome biases that results from single method, single observer, and 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 status of reliability by providing 'research grade' through community consensus, as mentioned above, which can also be an effective method to ensure 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 interobserver 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 data sets[105]. Project teams decide to make these adjustments based on 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 in the sampling tools and protocols. For example, REF.[107] collect anonymous geographic 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 commonly used methods to address them.

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[77,84,225] 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 (e.g., 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 interests[226,227] Triangulation across communities, participants, and methods[66]

Analyzing

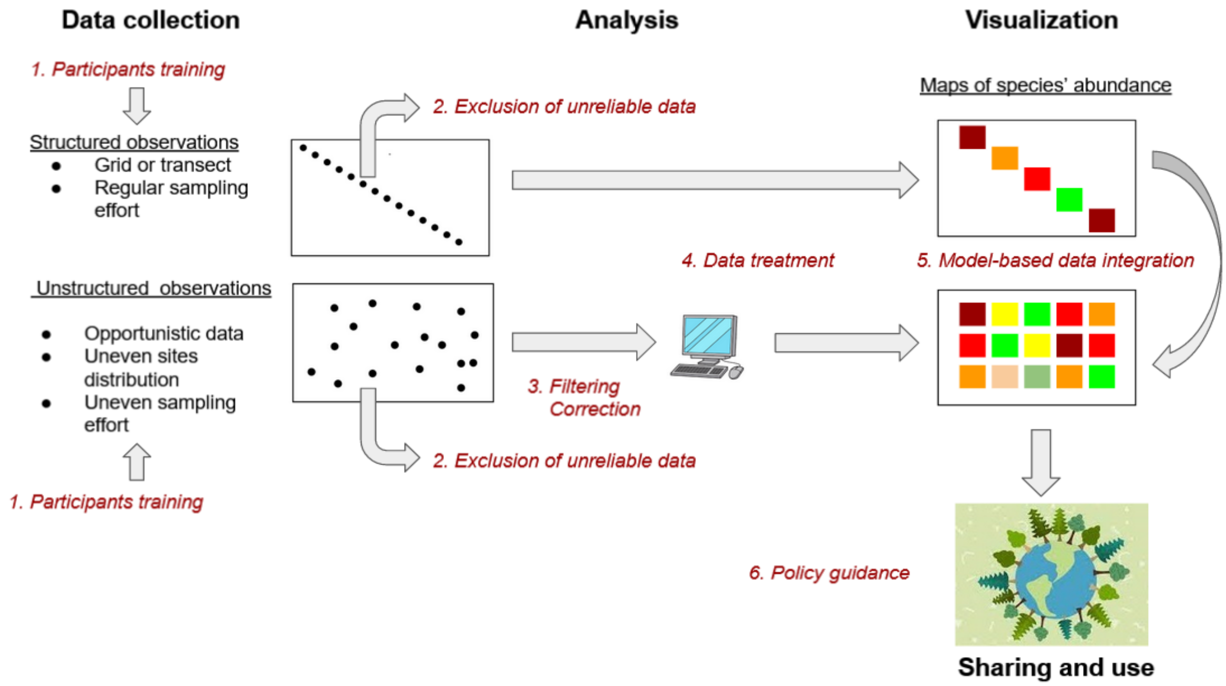
Analyzing the data generated by participants should be planned ahead based on the project goals and data needs. Various tools and methods exist to support data analysis in citizen science that depend largely on the type of observations.

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 analyzed 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 analyzed to generate patterns of abundances by counting the observed number of species of a given group, or individuals of a given species. Different types of analyses 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-dimension grids[111,112]. Structured data are commonly analyzed 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 biological records, are generally collected at higher quantities but specific statistical tools may be needed to render reliable abundance indices from individual observation efforts[115,116]. REF.[23] propose a set of methods based on data filtering or correction factors to account for the variation in recorder activity and uneven observation sites. Also, model-based data integration has emerged as a powerful approach to combine heterogeneous data sets[117]. FIG. 2 illustrates a stylized workflow for analyzing quantitative measures of species abundance based on structured and unstructured data collection as part of citizen science projects to monitor biodiversity.

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 which 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 render 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).

Dynamics of ecosystems

Citizen science data may also be analyzed to study more complex dynamics of ecosystems, using statistical, computing, 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 of 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 assess the role of floral morphology in flower-feeding[119].

Other citizen science data are constituted by material samples, such as fecal pellets, leaves, or soil samples[120]. They can be analyzed 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 visualisation 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 data set of the project, or to identify data gaps[126]. Data visualization also allow participants to become more active in different steps of data collection and analysis[127].

4 Application

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, amongst others, 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-tested method[3]. We complement these examples with applications in 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).

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].

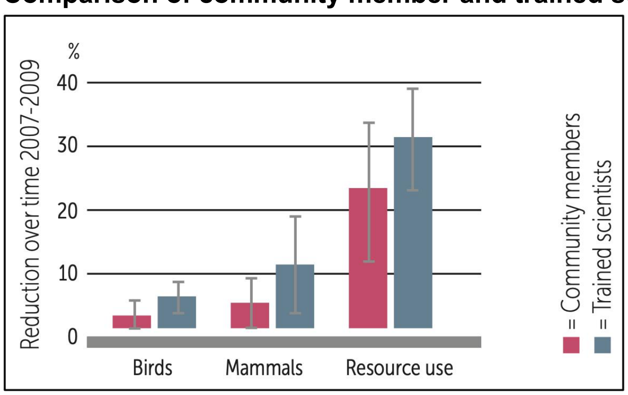
When members of the public are concerned about the environment and status of natural resources in an area, they sometimes want to lead and drive the research process related to the concern. Community-led citizen science (CCS) programs involve them in several stages of the research process beyond data collection, while professional scientists may provide advice and training[41,228].

CCS can be demanding in terms of the time and effort required of participants and scientists but the potential benefits to those involved are significant. The full-participation approach can provide time and place specific data at low cost that are trusted by those concerned and involved[229]. It 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, it can help generate transparency, accountability, and local ownership of resource management initiatives, empowering community members and prompting locally meaningful actions[66,230].

CCS programs 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 North[231], including the Arctic[232], in environmental justice[233], and other community-based initiatives[234]. It is particularly suitable where policy environments allow full or partial community control over resource management[66]. Programs 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 programs include getting authorities to respond to data and proposals and overcome reluctance to relinquish authority[237]; ensuring collective action and public participation[164], particularly when programs 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 they can provide reliable information independent of professional scientists and similar quantitative results on, for example, status of and trends in the abundance of species and natural resources information (see the figure). 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 and challenges into account.

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



Box 2: Collaborative Creation of Scientific Knowledge – Cientificos de la Basura

The Cientificos de la Basura ("Litter Scientists") program 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 program 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. S4). 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 behavior, and it is emphasized that these activities should be part of wider and more integral programs fostering scientific learning and promoting environmental stewardship[244,245].

The schoolteachers are the principal allies in the program, they are regularly trained by the professional scientists, and personal communication is maintained throughout the program activities. Teachers also submit the observations to the scientific team, and they are the 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 publications (supplementary FIG. S4) and shares them via media outlets with the public, and decision-makers[246–248].

The data have contributed to formulate or improve national laws on waste management[249]. They 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 program has been replicated in Germany[250,251], where the sister program, Plastic Pirates, is currently expanding to work with schools from other European countries.

Biodiversity research

Biodiversity-related research is prevalent amongst citizen science projects[3]. Citizen science projects, at the same time, have become a significant factor in biodiversity research, historically[130,131], and contemporarily[22], with a focus on species monitoring, contributing at least 50% of observations to international and global biodiversity databases, such as GBIF[132,133], although at times remaining unrecognized as a significant contribution to these efforts[134]. One format for a biodiversity-focused, contributory citizen science activity which has gained popularity and traction in recent years is the so-called BioBlitz, such as the Great Southern BioBlitz, with more than 270 local and regional initiatives in the southern hemisphere contributing more than 190,000 biodiversity observations across the southern hemisphere in 2021. Despite some of the known challenges, citizen science presents vast opportunities for application in biodiversity research, including among others, improving undersampled taxa and regions, among others, 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

Scientific Aims

MammalWeb began in 2015 in north-east England, United Kingdom, but 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].

Data Gathering and Quality Control

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. S1). Collected photos and videos are uploaded with spatial-temporal METADATA to MammalWeb and classified by registered users. Images of humans are removed from the classification pool immediately after being flagged.

Data Analysis

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 allow profiling 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 behavior, 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].

Engagement Strategy and Ethics

Other conservation organizations are now hosting camera trapping projects on MammalWeb. This expands the geographical coverage, decentralizes the organization of participants, and shows 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].

Results and Insights

Over 270 participants across eight European countries have contributed data to MammalWeb. The network includes more than 50 schools and 20 additional organizations. These 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 locate potentially invasive species including raccoon and coati[144]. 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 modeling of human classifications to improve accuracy of derived data as well as the realization that the most engaged participants are highly motivated and move towards co-created citizen science, which should be welcomed by scientists.

Spipoll

Scientific Aims

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 of plant pollinator interaction in space and time across France[147].

Data Gathering and Quality Control

Participants follow a standardized protocol, which does not require any prior knowledge about insects. Wherever participants can find a flowering plant from dense urban centers to natural areas, they take pictures of all invertebrates landing on its flowers during a 20-minute period. After having identified insects and plants using a dedicated online identification tool, they upload their pictures and associated identifications, as well as date, time, location of observations, and climatic conditions to the Spipoll website. Quality control was originally exclusively made by expert entomologists, who validated insect identification. Since 2019, a collaborative quality control system was implemented, which now allows participants to validate observations submitted by others, as illustrated in supplementary FIG. S2.

Data Analysis

Data sets are analyzed to quantify the composition of visiting insect communities, depending on flower family and environmental factors. These results are then interpreted in terms of plants-insects 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 insects' orders[118,148].

Engagement Strategy and Ethics

To ensure long term engagement of participants, yearly meetings are organized with researchers from MNHN and community managers from OPIE. Weekly news including 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].

Results and Insights

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 favorable pollinator habitats[148]. Datasets are available under open access licenses. Spipoll's online communication spaces for participants contribute largely to the constitution of a friendly learning community, help retain them in the long-term as well as help improve data quality[97]. As such, Spipoll illustrates the key role of such online interaction and participant support tools to achieve contributory citizen science's multiple goals.

Participatory Guide of the Marine Species in the Barcelona Metropolitan Area

Scientific Aims

Conserving biodiversity near urban beaches is challenged by increases of 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, Anel·lides Environmental Services, engages participants to monitor and understand the factors affecting biodiversity in beaches around the Barcelona Metropolitan Area.

Data Gathering and Quality Control

Observations are collected mainly in guided snorkeling tours offered by Anel·lides Environmental Services, which provides local knowledge and logistics support, such as masks and underwater cameras. Photos collected during snorkeling 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 Analysis

Data are analyzed by the ICM researchers to identify differences in the composition of ecological communities and link those to the anthropogenic impacts. The first estimation of the species richness[149] was obtained with an approach based on unique observations and the species list[150].

Engagement Strategy and Ethics

The project has been promoted particularly through the social channels of the Anel·lides Environmental Services, exploiting the guided scientific snorkeling tours as a market opportunity. Most of the participants did not have prior knowledge on marine organisms. Tours with guided specialists ensured the correct use of equipment and safety conditions, as well as the best suitable places to explore depending on the sea conditions (supplementary FIG. S1). In some cases, they also provided innovative learning activities for schools[151].

Results and Insights

The project led to the first Participatory Guide of Marine Biodiversity in the Barcelona Metropolitan area[152] and helped to provide a baseline dataset on 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 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 practices of citizen science appear under different terms. These include Volunteered Geographic Information[154], Crowdsourced Geographic Information[155], and most recently, Geographic 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

Scientific Aims

FotoQuest Go aims to collect ground-based observations on land use and land cover across Europe. A specific question was to identify whether citizen science participants can collect as high-quality observations as those collected by professionals at a lower cost and 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].

Data Gathering and Quality Control

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, 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 to improve it next time. Short training videos provide information on how the app works, how the user can make and submit quality observations, and how to identify different crop types to further improve data quality (supplementary FIG. S1).

Data Analysis

FotoQuest encourages each participant to visit several locations. This implies that observations provided by the same participant are not independent from each other. Simultaneously, the closer the locations are to each other, the higher the spatial autocorrelation is. 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].

Engagement Strategy and Ethics

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 between one to three Euros, 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 are collected, how they are stored and used, and how they 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].

Results and Insights

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 behavior 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], 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.

The Forest Health Watch / Western Redcedar Dieback Map

Scientific Aims

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. 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 (climate, soils, and topographic data) to classify trees as healthy or unhealthy.

Data Gathering and Quality Control

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 Analysis

Data shared on iNaturalist are combined with the 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 overcome a common challenge of biodiversity studies, namely the documentation of the absence of an organism with confidence[179].

Engagement Strategy and Ethics

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

Results and Insights

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 close to 200 participants were collected for the WRDM project (see the data and information dashboard of WRDM in supplementary FIG. S4). 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.

5 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

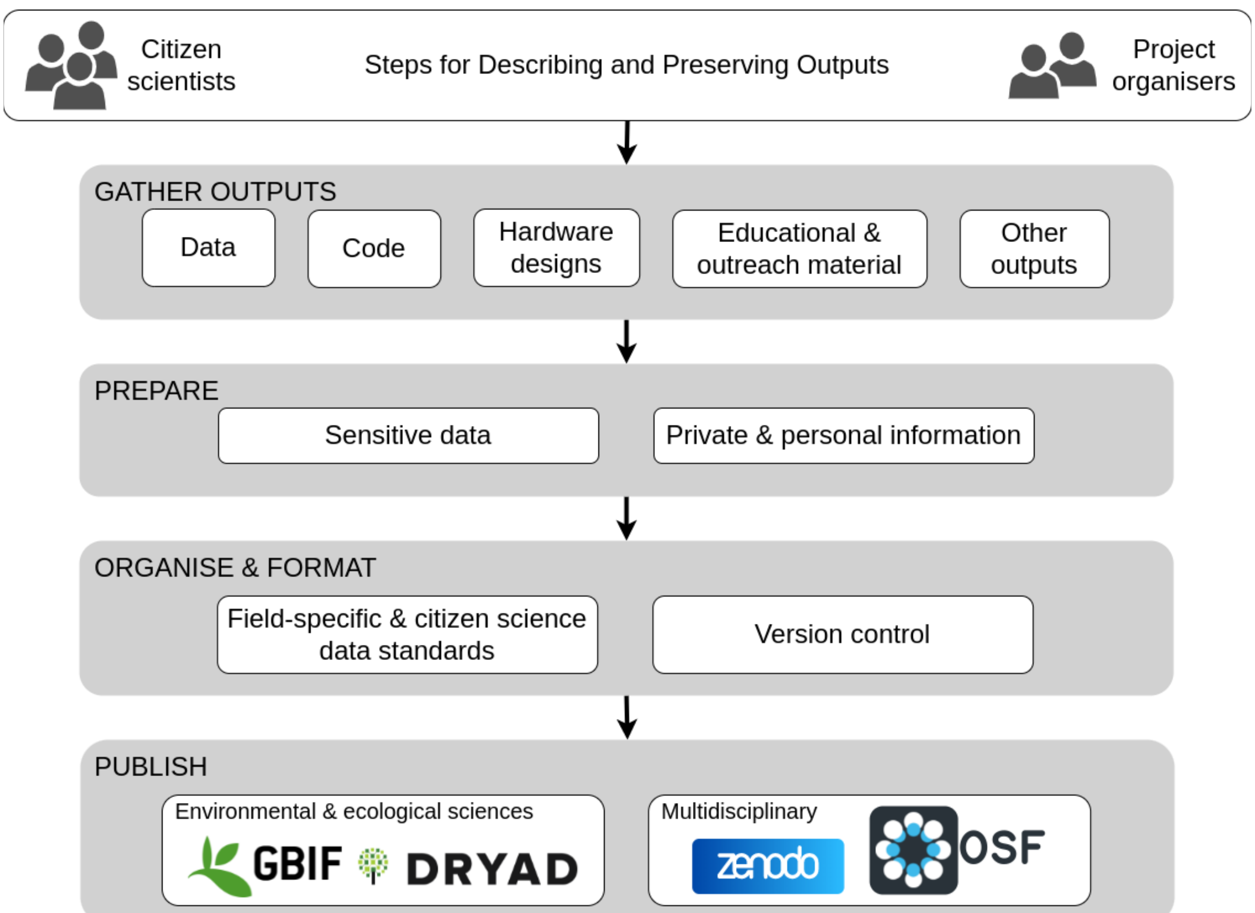
Data and other outputs from citizen science should be described, documented, and shared with permissions to ensure reuse and reproducibility[180], but it is important to consider what data to share and how to share them[133]. For example, sharing the precise location of endangered species might inadvertently aid illegal poaching. Sharing of citizen science data also poses ethical issues regarding data privacy[181] or data sovereignty of individual participants[35]. Thoughtful preparation, such as lowering the resolution of coordinates in spatial data or obscuring personally identifiable information, helps data sharing to serve multiple scientific and policy-related purposes. These include characterizing 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 on 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 is essential to facilitate data sharing and reuse, which is referred to as metadata. 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 maximize the value of the data. It offers a common format for data storing, description, as well as interoperability and integration with other data sets. Rich metadata and data practices also support FAIR data principles (Findable, Accessible, Interoperable and Reusable), 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 programs[35,95]. The CARE principles for Indigenous Data Governance (Collective benefit, Authority to Control, Responsibility and Ethics) offer a framework 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. FIG. 3 illustrates the process for publishing outputs from a citizen science project.

Fig. 3: Best-practice steps for publishing outputs from a citizen science project



The depicted steps fall within the Describing and Preserving Data step in Stage 5 of a citizen science project plan (see FIG. 1): 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.

Equally important are software and hardware outputs. Reproducible code best practices 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 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 data set 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 these 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) licenses 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 this way, not just the 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.

6 Limitations and optimizations

Citizen science has a range of 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 of 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 the intended research subject not being interesting to the target audience. Additionally, in some contexts with high social inequality, citizen science is likely to engage only certain parts of society, failing 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 skills to do so[62,195,196].

Every source of scientific data, including data from citizen science, comes with specific biases. It is important to be aware of these biases, and work to mitigate them through attentive design and data analysis. One very common bias in citizen science is introduced by non-expert contributions, raising the question of whether non-professional participants can produce accurate data sets. As discussed previously, there are various ways to 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 common bias in citizen science is related to population density with places that have high populations are more likely to be monitored[198]. Similarly, road networks have an impact on the locations that can be easily accessed and monitored[199]. There are also temporal biases, such as the daytime and weekend biases[56,200,201]. Additionally, biases related to participant contributions are common in which a relatively very small number of participants provide a significant proportion of the data[202]. Moreover, biases in the profile of participants, such as education, age, and gender can influence the coverage and wider impact of a project[203]. When the observations are sensor-

based, citizen science projects will mostly use low-cost sensors, frequently those that are integrated into smartphones or reappropriated from another areas of practice such as automotive applications. The limitations and biases of these sensors need to be addressed considering their purpose of use, such as raising awareness on a particular issue within a community or contributing to policy making, among others[204]. To address these biases, existing literature can help identify what they are as well as find solutions to them.
Varying data protection laws in different countries can also be a limitation in citizen science. While deciding about which data to collect and share in a project, it is important to identify the relevant laws and regulations of the country or countries in which the project operates and to comply with them. It is recommended to consider what data are essential for the project at the design stage of a project. For example, the EU GDPR presents the data minimization principle, which highlights that data collection should be adequate, relevant, and limited to what is necessary in relation to the purposes for which they are processed[161].

Additionally, there may be limitations related to designing and implementing citizen science projects in remote and unsafe areas, where mobile network coverage is poor, access to smartphones and power 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 (see also BOX 1)[205].

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, potential risks should be considered and clearly communicated to the participants along with information on how to avoid them. TABLE 4 provides a list of potential limitations of citizen science and strategies to overcome them.

Table 4: Examples of potential limitations in citizen science and recommendations on how to overcome them

Examples of Limitations	Recommendations on how to overcome them	Related design and implementation stage
Required wide range of skills outside of the research subject	Establishing partnerships with other project teams and stakeholders conducting similar projects and activities Working 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	Understanding the participant motivations at the design stage Creating tasks that appeal to different motivations Integrate tasks into the existing day-to-day activities of the participants[35] Facilitating participant feedback and exchange throughout the	Stage 4: Building the community

	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]	
Bias related to the quality of non-expert contributions, and accordingly the risk of citizen science not being recognized as a legitimate source of knowledge in decision-making	See TABLE 3 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 analyzing)
Bias related to human population density	Examining the literature to identify potential biases and how they could influence 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 analyzing)
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		
Varying data protection laws in different countries	Consider what data are essential for the project at the design stage of a project. For example, the EU GDPR presents the data minimization principle[161]	Stage 3: Designing the project Stage 5: Managing the data (steps related to planning, collecting, assuring, analyzing, and 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, e.g., loss of smartphones, visiting locations that are remote or unsafe, political risks, etc.	Clearly communicating 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)

7 Outlook

The fields of application for citizen science methods and approaches continue to broaden in terms of subject matter and deepen in terms of the advancement of 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 know-how, and nurturing collaborations across disciplines and across borders. Over the coming years, these associations will likely continue to expand to under-represented countries and regions to connect grassroots practitioners with the wider community of practice, introducing new insights from unique geographical contexts and diverse stakeholder groups. This is of great importance not only for social inclusiveness, but also for reaching out to those parts of the world, where the greatest data gaps on environmental knowledge exist. Achieving this requires significant 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 members of the public 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 in seeking 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 examined issues, namely, providing insights for better environmental management, providing data evidence for policy making, inspiring behavior 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 "extends well beyond development and testing of research hypotheses, including activities such as environmental monitoring, producing training data for supervised machine learning, data visualization and interpretation, and complex problem solving".

Some of the barriers to citizen science becoming a more mainstream research practice include low levels of awareness of the value and impact of citizen science, lack of support and recognition for career researchers in pursuing citizen science approaches, and 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 impactful 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 "extending collaborations between scientists and societal actors beyond the scientific community, by opening up practices and tools that are part of the research cycle and by making the scientific process more inclusive and accessible to the broader inquiring society based on new forms of collaboration and work 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 SDGs, where at least 33 percent 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 per cent 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[252].

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 shone a light on only one small segment of this rapidly growing field, and we look forward to the new innovations and transdisciplinary collaborations that will be introduced by researchers and project leaders over the years to come.

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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).
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This article highlights benefits of linking community- and science/policy-led approaches.

Related links

US Citizen Science Association: https://citizenscience.org/
European Citizen Science Association: https://ecsa.citizen-science.net/
Australian Citizen Science Association: https://citizenscience.org.au/
CitizenScience.Asia: http://www.citizenscience.asia/
Citizen Science Africa Association: https://www.usiu.ac.ke/citsci-africa-association/
Global Citizen Science Partnership: http://globalcitizenscience.org/

"Data Visualisation Overlay" from the SPOTTERON citizen science platform: https://www.spotteron.net/blog-and-news/making-data-meaningful-data-visualization-overlay-in-citizen-science-apps-on-the-spotteron-platform
CesiumJS open-source JavaScript library: https://cesium.com/platform/cesiumjs/
CWDAT open-source tool: https://spatial.wlu.ca/cwdat/

Great Southern BioBlitz: https://www.inaturalist.org/projects/great-southern-bioblitz-2021-umbrella
MammalWeb project: https://www.mammalweb.org/
Spipoll project: https://www.spipoll.org/
URBAMAR project: https://www.natusfera.org/projects/urbamar
Atlas of Barcelona Biodiversity: https://ajuntament.barcelona.cat/atlesbiodiversitat/en/
FotoQuest Go: https://fotoquest-go.org/
The Western Redcedar Dieback Map (WRDM) project: https://www.inaturalist.org/projects/western-redcedar-dieback-map
Forest Health Watch program: https://foresthealth.org/
Community-based Monitoring Library: https://mkp28.wixsite.com/cbm-best-practice
Cientificos de la Basura program: https://www.cientificosdelabasura.cl/
Plastic Pirates: https://www.plastic-pirates.eu/

Public Participation in Scientific Research (PPSR) Core: https://core.citizenscience.org/
Darwin Core: https://dwc.tdwg.org/
The Zooniverse GitHub: https://github.com/zooniverse/
iNaturalist GitHub: https://github.com/inaturalist/
Dryad data repository: https://datadryad.org/stash/
OSF repository: https://osf.io/
Zenodo repository: https://zenodo.org/
Registry of Research Data Repositories: https://www.re3data.org
Cos4Cloud project: https://cos4cloud-eosc.eu/
European Open Science Cloud: https://eosc-portal.eu/
choosealicense.com: https://choosealicense.com/
CERN Open Hardware Licences: https://ohwr.org/project/cernohl/wikis/Documents/CERN-OHL-version-2
Creative Commons licenses: https://creativecommons.org/about/cclicenses
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
National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Monitoring and Assessment Project's Accumulation Data: https://mdmap.orr.noaa.gov/

European Environment Agency’s Marine Litter Watch: https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch/data-and-results/marine-litterwatch-data-viewer
Ocean Conservancy’s International Coastal Cleanup (ICC) Trash Information and Data for Education and Solutions (TIDES): https://www.coastalcleanupdata.org/

Citizen Science Center at the University of Zurich: https://citizenscience.ch/en/
EU-Citizen.Science platform: https://eu-citizen.science/
AfriAlliance Knowledge Hub: https://afrialliance.org/knowledge-hub
Iberoamerican Network of Participatory Science (RICAP): http://cienciaparticipativa.net/la-ricap/
Public Lab: https://publiclab.org/
Safecast: https://safecast.org/

Glossary terms

*) First appearance in main text

Term	Description
Introduction section*)	
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 analyze 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[229].
Contributory Citizen Science	Citizen science programs designed by professional scientists and involving non-credentialed participants primarily in contributing to data collection.
Experimentation section*)	
In-situ	In-situ refers to data that is gathered ‘on a site’, an activity that takes place locally, or an observation made at a specific location on the ground.

Term	Description
Opportunistic data	Opportunistic data is 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.
Results section*)	
Structured/ semi-structured/ unstructured	Citizen science programs 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.
Application section*)	
Community-led citizen science	Citizen science programs 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.
BioBlitz	A collective activity, most often open to the public, to record biodiversity observations within a set timeframe 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.
Reproducibility and data deposition section	
Limitations and optimization section	
Outlook section*)	

Term	Description
Citizen Observatories	Community-based environmental monitoring initiatives that gather citizen science data for policy-making, and environmental management and governance.

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Competing Interests

There is NO Competing Interest.