Mapping the state of the art to envision the future of large-scale citizen science projects: an interpretive review

Anonymized for peer review

Abstract

Citizen science, *i.e.* citizens' involvement in research activities, is achieving an increasing relevance across different scientific domains. However, literature is not consistent in arguing citizen science's attributes and implications when large scale projects are concerned. The article systematizes extant scientific knowledge in this field and identifies avenues for further developments through a bibliometric analysis and an interpretive review. Various approaches to citizen science are implemented to engage citizens in scientific research. They can be located in a continuum composed of two extremes: a contributory approach, which serves research institutions' needs, and an open science approach, which focuses on citizens' active participation in knowledge co-creation. Although contributory citizen science paves the way for participatory science, it falls short in empowering citizens, which is central in the open science approach. Interventions aimed at enabling citizens to have an active role in co-creating knowledge in a perspective of science democratization is key to overcoming the understanding of citizen science as a low-cost model of scientific research and to boost the transition towards an open science approach.

Keywords: Citizen science; Participatory research; Large-scale research; Citizen engagement; Citizen involvement

Introduction

A transition towards Society 5.0 is reshaping the functioning of institutions across the world (Fukuyama, 2018), aiming at the establishment of a "*...human-centered society in which products and services will be readily provided to satisfy various potential needs as well as to reduce economic and social gaps so that all the people live a comfortable and vigorous life*" (Fukuda, 2020: p. 1). In line with this overarching purpose, Society 5.0 embraces a peer-to-peer perspective to reconceptualize the paradigms inspiring individual and collective actions (Malecki, 2017; Wildschut, 2017). This happens in a variety of contexts, including public services provision and knowledge creation (Gladden, 2019). Scientific research has anticipated other domains in the application of the principles underpinning the transition towards Society 5.0 (Tsukahara, 2017). *Inter alia*, citizen science represents a powerful way of achieving human centeredness in the realm of scientific research (Silvertown, 2009). It rethinks the relationship between research institutions and people (Wechsler, 2014), entailing "*…the general public engagement in scientific research activities when citizens actively contribute to science either with their intellectual effort or surrounding knowledge or with their tools and resources*" (European Commission, 2013: p. 6).

Many labels have been used to refer to citizens' engagement in scientific research, such as: participatory science, crowd science, volunteer science, community science, and networked science (see, among others: Rahm *et al*., 2005; Nielsen, 2012; Franzoni and Sauermann, 2014). In general terms, citizens' engagement involves the establishment of collaboration on a voluntary basis between citizens and expert scientists to cope with scientific issues which could not by addressed by relying on the processing capabilities possessed by a single research institution exclusively (Follett and Strezov, 2015). Furthermore, it is intended to support people in getting knowledgeable about timely and relevant scientific issues, inspiring their decisions and actions in daily life (Sharma *et al*., 2019). Drawing on these considerations, citizen science, which involves both a focus on people's contribution of "*...observations or efforts to the scientific enterprise*" and an emphasis on "*…the responsibility of science to society*" (Eitzel *et al*., 2017: p. 6), can be understood as an umbrella concept referring to the establishment of a co-creating partnership between citizens and expert scientists for the purpose of knowledge co-production (Wagenknecht *et al*., 2021). This makes citizen science something more as compared to alternative approaches giving voice to citizens in the generation of scientific knowledge, such as Do It Yourself (DIY) science (Nascimento *et al*., 2014), which "*…broadly refers to the process initiated by individuals and groups that tinker, hack, fix, and recreate objects and systems out of their own interest, curiosity or need, and openly share results and outcomes in their networks*" (Ferretti, 2019: p. 4).

Although citizen science has deep historical roots and it has been applied to manifold scientific areas, including astronomy, biology, ecology, geography, health science, and physics (see, among others: Cornwell & Campbell, 2012; Panofsky & Donovan, 2019; Hielscher & Jaeger-Erben, 2021), its features are especially fitting with large-scale projects (Lintott, 2020). They include those research endeavours that are characterized by huge number of researchers and broad range of discoveries that are either directly or indirectly related to the achievement of the main research aims. Citizens' engagement in such projects serves three main functions, which are related to the transition towards a peer-to-peer society (Wildschut, 2017): 1) collection of rich databases, especially when micro-local phenomena are investigated; 2) cross-validation of evidence obtained by expert scientists; and 3) democratization of knowledge.

Scholars quarrel in debating the future of citizen science in large-scale research projects (Roe, 2021; Peters & Besley, 2022). Actually, doubts about the added value of citizen science have been raised, with public engagement in scientific endeavours being presented in several circumstances as a populist rhetoric (Woolley *et al*., 2016). To systematize these diverging propositions, the article proposes a bibliometric analysis and an interpretive literature review, which features the state of the art about the triggers and the characteristics of citizen scientists' involvement in large-scale projects. Two research questions, inspired this study, which primarily aimed at envisioning the future of citizen science in large scale scientific research:

> *R.Q. 1*: What are the steps to citizens' engagement in large-scale scientific research projects?
>
> *R.Q. 2*: What are the implications of citizens' involvement in large-scale scientific research projects?

The article proceeds as follows. Next section delivers some information about the research protocol which was used to select relevant items to be included in this literature review. Then, the research findings are reported, which summarize the state of the art of extant scientific debate about citizen science in large-scale research endeavours. Research findings are critically contextualized and systematized in the discussion section, which paves the way for the main study implications and for avenues for further development, as argued in the concluding part of this paper.

Methods

Study design

A mixed methodology was designed to provide answers to the research questions inspiring this study. A bibliometric analysis was undertaken to obtain an overview of extant scientific knowledge contextualizing citizen science to large-scale research projects. Next, an interpretive approach was implemented to systematize the study findings and to envision avenues for future developments. Drawing on Paul and Criado (2020), a domain-based perspective was embraced to implement the literature review. This allowed us to obtain a state of the art representation of a substantive research field, that is to say citizens' engagement in accomplishing large-scale research endeavours (Palmatier *et al*., 2018).

The Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) protocol developed by Paul *et al*. (2021) was followed. In particular, the study design consisted of three steps. During the first stage (Assemble), the corpus of literature was identified and relevant records were collected. The main intent of this step was to fetch a satisfactory volume of items that were consistent with the study aims. In the second step (Arrange), codes were crafted to steer the analysis of retrieved items. Multiple peer discussions were placed amongst the authors to define the inclusion and exclusion criteria for purifying the dataset from records which did not completely meet the study purpose. In the last step (Assess), selected items were evaluated and the research findings were reported. More specifically, the study results consisted of: 1) a clusterization derived from bibliometrics; and 2) an interpretive literature review based on the narrative approach proposed by Tranfield *et al*. (2003).

Assemble

Literature search started in February 2020. A tailored search strategy was articulated to establish a representative list of terms that allowed us to address the study aims. This procedure was decisive, as the inclusion or exclusion of a single term could result either in an excessively limited or in a vainly extensive set of contributions. After several trials, the authors agreed on the most significant terms to elicit the broadest spectrum of concepts that preview directions of research in the field of citizen science applied to large-scale scientific research. In an attempt to include all relevant contributions, additional topics that resemble citizen science were contemplated, including crowd science, participatory science, civic science, volunteer science, and networked science (Randhawa *et al*., 2016). Since the focus of this paper was on the direct involvement of citizens in scientific endeavours, more generic concepts such as public participation and public engagement with science were not taken into account (Stilgoe *et al*., 2014).

The selection procedure for the most suitable citation database required the involvement of all the authors. After several meetings, authors unitedly agreed on opting for Web of Science™ and Scopus®, as they are considered the most reliable sources for bibliometric purposes (Ding *et al*., 2016). A comparison was made between the two databases. The cross-validation results revealed that Web of Science indexed a larger number of relevant studies which were consistent with the study aims. Therefore, it was chosen as the main data source for this analysis. The identified key terms were executed through a Boolean search query. The search string, which was run on March, 29th 2020, follows:

TS=("Citizen Science" OR "crowd science" OR "Participatory science" OR "civic science" OR "volunteer monitoring" OR

"Volunteer Science" OR "Community Science" OR "networked science" OR "Citizen participation" OR "Citizen involvement" OR "Citizen Engagement" OR "citizen scientist") AND TS=("Big science" OR "Large scale" OR "Research infrastr")*

The "TS" operator runs a search on title, abstract, or keywords. The search was limited to "articles" and "reviews" as document types. This permitted us to include in the analysis only peer-reviewed documents that are acknowledged as certified knowledge (Ramos-Rodríguez & Ruíz-Navarro, 2004). No other limitations were assigned. As a result of the assemble step, 287 documents were initially collected.

Arrange

A multi-step procedure was implemented to refine the dataset. Retrieved documents were stored in an electronic worksheet, which was shared among the authors. Items were independently read in order to perform a preliminary screen. Three exclusion criteria were set: 1) items which did not show a direct relationship with the research aims were retracted as "off topic"; 2) items which did not have a direct relationship with the research scope were retracted as "off scope"; and 3) items which did not provide us with compelling management and practical implications about citizen science targeted to large-scale scientific research were retracted as "off focus". Two rounds of refinement were implemented. Firstly, attention was focused on items' titles, abstracts, and keywords. As a result of this preliminary screening, 130 papers were dropped. The second round focused on the specific contents of the included contributions, which were examined in their full text: 1 item was found to be not consistent with criterion 1); 28 items were removed according to criterion 2), and

15 were omitted considering criterion 3). Therefore, at the end of the arrange step, the finalized dataset included 113 relevant and impactful papers.

Assess

A bibliometric examination based on the Visualization of Similarities (VoS) technique was realized to assess the items. VoS identifies homogeneous themes within body of scientific literature through citation relations. The core part of the analysis was implemented in VoS viewer, *vers. 1.6.10* (Van Eck & Waltman, 2010). The aggregation algorithms primarily relied on bibliographic coupling: two documents are bibliographically coupled when they both cite one or more common documents. Reference overlap between two items implies their inclusion in the same cluster. VoS technique kicks off with the generation of a similarity matrix, which is developed by normalizing a co-occurrences matrix of common references. The script displays a two-dimensional map for all items, which are located in accordance to their similarity measures. No limitations were set for the VOS viewer's parameters. The items' distance can be interpreted as the relatedness between them: the closer they are, the stronger their connections. However, 9 papers were not involved into the similarity analysis. The link strength of these items was realized at zero and, therefore, they were omitted from the analysis.

As reported in Figure 1, which displays a flowchart representing the steps of this literature review, 104 records were included in the analysis. Based on cluster analysis, a narrative approach was used to interpret clusters and to shed light on avenues for further development. Manual coding was implemented to obtain evidence of the specific contents of each cluster. In particular, coding activities were based on two aims: 1) shedding light on the steps taken to engage citizens in large-scale research endeavours, and 2) gauging citizens' contribution to the advancement of scientific knowledge. The authors had a meeting to achieve a consensus on the codes used to report the study findings. In sum, 6 codes were identified, concerning: 1) the drivers of citizen science; 2) the design of citizen science projects; 3) the configurations of citizens' involvement in scientific research; 4) the implications of citizen science; 5) the citizens' contribution to knowledge co-creation; and 6) the durable engagement of citizens in scientific research. The codes identified by the authors were associated to the clusters delivered by the VOS aggregation results. Furthermore, a keyword analysis was implemented for observing the most influential terms, which were conceptually connected to the 6 identified clusters. This allowed us to point out the focus of each research stream retrieved in the literature review and to emphasize bridges between different clusters, illuminating the *whys* and the *hows* of citizens' engagement in large-scale scientific research.

[Please, insert Figure 1 about here]

Findings

Overview of the items

As reported in the previous section, the bibliometric analysis relied on a database composed of 104 records. The majority consisted of regular articles published in peer-reviewed journals (91.3%). Only 1 item was a conference proceeding included in a special issue of a peer-reviewed journal. The remaining part was composed of review articles (7.7%). None of such review articles dealt with topics which either totally or partially overlapped the focus of this study. The records were distributed in a variety of venues. The disciplinary areas contemplated in this literature review included, *inter alia*: astronomy, biology, computer science, earth science, ecology, and medicine. This highlights the transdisciplinary nature of citizen science. Publication years ranged between 2008 and 2020. About two in three items were published in the last five years (65.4%). This stresses the timeliness of the research topic. On average, the items had 26.7 citations (σ = 75.7), ranging from 0 citations to 687 citations. The papers which had no citation were published in the five years preceding this research. Most of them (80%) were published between 2019 and 2020.

Cluster analysis

Figure 2 shows the results of the clusterization analysis. Six clusters were identified. The intertwinement between the clusters suggests that the different research streams identified by the VOS analysis were mutually related by several conceptual bridges. The average number of citations for each cluster was 462.2 (σ = 382.7), ranging from a 62 citations to 1,273 citations. Clusters were transdisciplinary and none of them exclusively listed items related to a specific scientific domain. It is worth noting that the inclusion of items in the clusters was not affected by publication years. Clusters dealt with two predominant topics, that matched the study purposes: 1) the steps that lead to the design and implementation of successful large-scale citizen science projects; and 2) the implications of citizens' involvement in scientific research.

[Please, insert Figure 2 about here]

Figure 3 shows a co-occurrence matrix of the 100 most recurring keywords which were retrieved in our bibliographic analysis. Keywords were conceptually related to the 6 clusters which were identified in this literature review. The yellow cluster concerns the triggers of citizen science. More specifically, it addresses the reasons motivating citizens to participate in scientific research as data collectors and analysts. Such reasons primarily involve the contribution to the improvement of quality of life and to the preservation of environmental integrity. Next, the blue cluster reviews the steps which can be envisaged in the process of citizens' engagement in scientific research. Actually, involving citizens requires some preliminary steps, which encompass citizen scientists' education and training in an attempt to sustain their ability to factually partake in scientific research. The red cluster presents the modes and the approaches of citizen science, emphasizing that web-based platforms and Information and Communication Technologies (ICTs) pave the way for greater opportunities of exchange between expert scientists and citizens. The green cluster critically reports the implications of citizen science, which may lead to some unexpected results, such as the collection of unreliable data or the misidentification of relevant scientific issues. From this point of view, the purple cluster envisages some interventions which may be undertaken to address the shortcomings of citizen scientists, primarily focusing on large-scale research projects hosted by web-based platforms. Lastly, yet importantly, the cyan cluster looks at peculiar types of citizen science, including initiatives implemented in the health care field in order to envision effective solutions enhancing the retention of citizen scientists and exploiting the full potential of citizen science.

[Please, insert Figure 3 about here]

The yellow cluster: the *whys* of citizen science

Although citizen science appeared in scientific literature in the past few decades, citizens' involvement in scientific research has well-established historical roots. It has been conceived as a knowledge co-production approach to enhance scientific efforts accomplished by research institutions and to increase the public understanding of science (Miller-Rushing *et al*., 2012). In general, it is possible to identify two *whys* to citizens' participation in the co-design and co-implementation of scientific research. On the one hand, citizen scientists accompany expert scientists in realizing time-expensive research activities, which are critical to advance scientific knowledge (Dunham and du Toit, 2013). More specifically, citizen scientists expedite data collection and systematization, allowing expert scientists to obtain large and highly representative datasets to accomplish their research activities (Hiller and Haelewaters, 2019). On the other hand, citizen science represents a way to enhance the public awareness of what is happening in the scientific realm: it pushes public engagement with science and fosters the transition towards democratic science (Tuttle *et al*., 2015).

Adopting a management view, citizen science is exploited as a cost-effective method to support expert scientists in their research activities (Zilli *et al*., 2014). Citizens partake in a variety of tasks that are demanding for research institutions. Engaging citizens who are distributed in different geographical locations heightens the research institutions' ability to detect variations in phenomena under investigation timely, without adding relevant costs to research activities (Hiller and Haelewaters, 2019). Furthermore, citizens' involvement enables the creation of rich and extensive datasets, which derive from the multiple contributions of a myriad of data collectors operating according to protocols and guidelines issued by expert scientists (Birkin and Goulson, 2015). Also, citizen science is conducive to a better collection of evidence over time, paving the way for consistent longitudinal studies (Martay *et al*., 2018). Lastly, yet importantly, data collected by citizen scientists can be confronted with the datasets built by expert scientists, allowing to check the consistency of available evidence and to develop more reliable prediction models (Lin *et al*., 2019).

Conversely, embracing a democratic science view, involving people in scientific research is primarily targeted at the generation of social gains, which go beyond the management needs of research institutions. Public involvement entails collaborative learning, that enhances citizens' appreciation and acknowledgement of scientific developments, thus supporting the democratization of science (Hod *et al*., 2018). Improving public awareness of scientific issues has two main spill overs: 1) from a macro perspective, it allows people to have a voice in inspiring the policy debate that is either directly or indirectly related to scientific issues addressed in citizen science projects (Van Brussel and Huyse, 2019); 2) from a micro perspective, it steers the advancement of scientific knowledge that is shaped by the collective contribution to unravelling scientific evidence (Loss *et al*., 2015).

The blue cluster: the *hows* of citizen science

Citizens' engagement in scientific research is a complex process, relying on hard (*i.e.*, structural) and soft (*i.e.*, behavioural) enablers (Locke *et al*., 2019). Citizen science applied to large-scale research projects entails the participation of a large amount of people in the accomplishment of scientific activities, including data collection and classification. Since these activities are usually performed through digital tools, citizens' participation is established on an Information Technology (IT) backbone, consisting of web-based network portals, online toolkits, and cloud data repositories. Portals enact an integrated cyber-physical space which enables to gather citizens and to build a communication bridge between them and expert scientists (Borzee *et al.*, 2019). Online toolkits have a twofold purpose: first, they are used to standardize and routinize the activities assigned to citizen scientists, facilitating their coordination with expert scientists (Liebenberg *et al.*, 2017); second, they foster interpersonal exchanges and data sharing, which are beneficial to nourish a group spirit among citizen scientists (Schmitz *et al.*, 2018). Cloud data repositories disclose three main advantages: 1) they release the generation of large and rich datasets (Little *et al.*, 2016); 2) they permit to scale up crowdsourced approaches to data classification (Swan, 2012_a); and 3) they allow the limitless access of citizens to crowdsourced data (Swan, 2012_b).

Alongside hard tools, soft triggers are needed to attract citizens and to sustain their durable commitment to citizen science. A pairing between expert scientists' needs and citizen scientists' interests is necessary to motivate the latter and to encourage their active participation in knowledge co-production (Johnson *et al.*, 2014). The clearer the communication of mutual gains that citizen science may trigger for expert scientists (*e.g.*, enhancement of research capabilities) and citizens (*e.g.*, public understanding of science), the greater the attractiveness of initiatives aimed at involving citizens in scientific research (Hoover, 2016). Once citizen scientists have been involved, it is necessary to retain their participation. Transparency and trust act as two social enablers of retention: whilst transparency is conducive to a fair partnership between expert scientists and citizens, trust stresses the co-creating nature of citizen science (Ganzevoort *et al.*, 2017).

Transparency and trust postulate that citizen science is rooted in an ethical approach to science, which rejects the dominance of expert scientists over citizens (Wiggins and Wilbanks, 2019).

Scientific literature argues that four interventions are useful to match the hard and soft requisites to citizen science and to ensure the active involvement of citizens in scientific knowledge co-production. Coordinators overseeing and managing the exchanges between expert scientists and citizens are effective in fostering collaboration and in minimizing the risk that diverging expectations and mismatched contributions may generate value co-destruction (Requier *et al.*, 2020). Targetization and personalization of recruitment and retention strategies are needed to shed light on the expectations of citizen scientists and to design highly engaging participatory science projects (Hermoso *et al*., 2019). Compelling research protocols and standards should be set to support the dependability of citizen science and to avoid that targetization may have side effects on data consistency (Gouraguine *et al*., 2019). Lastly, citizen scientists' training is imperative to enhance their skills and to increase their ability to collaborate with expert scientists effectively (Barrows *et al*., 2018).

The red cluster: modes and approaches of citizen science

Citizen science initiatives can be metaphorically conceived of as knowledge ecosystems empowering citizens to support the achievement of relevant targets for the scientific community. However, the design of citizen science initiatives is affected by several epistemic tensions stemming from the potential dominance of expert scientists over citizens, as well as from a focus on the advancement of research institutions' capabilities and new discoveries rather than on public understanding of science (Kasperowski and Hillman, 2018). Scholars have warned that citizen science may be impaired by the primacy of expert scientists' needs and expectations: this restricts the role that citizens are able (and willing) to play in the making of scientific knowledge (Chiou, 2019).

Such tensions have led to the arrangement of multiple modes of citizen science. Broadly speaking, citizen science approaches can be articulated within a continuum which ranges between two extremes. The most common mode emphasizes the crowdsourcing nature of citizen science, with citizens performing a supporting function. In this case, four different tasks can be assigned to citizen scientists: 1) data collection: citizens are engaged in the construction of large datasets, adhering to the guidelines and protocols prepared by expert scientists (Just and Frank, 2019); 2) data classification: citizens cluster available data sticking to procedures that are set by expert scientists (Raddick *et al*., 2019); 3) data processing: citizens are involved in elementary data analysis, eliciting evidence from dataset previously refined by expert scientists (Jimenez *et al*., 2019); and 4) training of automated or deep learning algorithms: citizens accomplish simple activities – such as data labelling and validation – that are aimed at advancing machine learning tools and technologies developed by expert scientists to harness big data (Khan *et al*., 2019).

Several interventions are needed to foster citizens' participation in this contributory approach to citizen science. Simple instructions and easy to follow guidelines are required to enhance the coordination between expert scientists and citizens (Martin and Greig, 2019). Tailored incentives and rewards acknowledging the contribution of citizen scientists are useful to support their retention (Ogie, 2016). Gamification (*i.e.*: the reconfiguration of repetitive tasks related to data collection or classification as entertainment activities) nourishes lay people participation: this is consistent with the citizens' desire to merge their contribution to science with entertainment, which is key to nurture attraction and retention to citizen science projects (Tinati *et al*., 2017).

The contributory approach is only partially consistent with the aim of "*…connecting nonscientists to the authentic process of science*" attached to citizen science (Garbarino and Mason, 2016: p. 7). Achieving this aim involves a broader understanding of citizen science, which should be understood as an exploratory and open science approach. Embracing this perspective, citizens are acknowledged as peers by expert scientists, playing an active role to address scientific and societal challenges. Far from performing as mere contributors of scientific tasks issued by expert scientists, citizens are engaged in transformative research endeavours, which are not merely focused on data collection and classification, but include participation in co-designing research activities (Crain *et al*., 2014). In other words, open science tries to exploit the citizens' collective thinking, paving the way for a fully-fledged co-production of scientific knowledge (Yadav *et al*., 2019).

Many barriers prevent the transition towards an open science understanding of citizens' involvement in scientific research, such as lack of awareness of the impact of citizen science on knowledge generation and citizen scientists' poor motivation, inadequate skills, and limited self-efficacy. Hence, tailored interventions are required to implement an open approach to citizen science, such as: citizens' enablement through tasks' personalization (Khoi and Casteleyn, 2018); the design of attractive interfaces promoting exchanges between expert scientists and citizen scientists (Smith, 2014); the identification of small groups of engaged contributors acting as catalysts of community involvement in scientific knowledge generation (Spitzer and Fraser, 2020); and the acknowledgement of greater freedom and autonomy to citizen scientists, filling in their perceived gap from expert scientists (Mahr and Dickel, 2019).

The green cluster: the grey side of citizen science

Citizens' involvement in scientific research is not free of concerns (Lawson *et al.*, 2015). Engaging citizens in knowledge co-production generates both benefits and challenges for research institutions, that make it difficult to assess its overall implications (Dickinson *et al.*, 2010). In general, scholars agree in arguing that citizen science contributes to enhancing the collective awareness of scientific issues and to increasing the social legitimation of research institutions in a perspective of democratization of science (Jiguet *et al*, 2012). Nevertheless, only limited efforts have been accomplished to gauge such gains. Rather, most of the scholarly attention has been focused on the cost-effectiveness of citizen science and, therefore, on its contribution to the financial viability of research institutions (Heigl *et al.*, 2017).

Expanding the expert scientists' ability to collect and process spatially and temporally distributed datasets (Meehan *et al.*, 2019), citizen science allows research institutions to accomplish demanding activities by saving large number of resources (Farhadinia *et al.*, 2018) and time (Dennis *et al.*, 2017). By virtue of their broad distribution, citizen scientists enable the contextualization of research activities in micro-local contexts, without requiring the hiring of specialized collaborators (Steininger *et al.*, 2015). Furthermore, citizens are usually involved in the initial steps of the transition towards research activities based on big data analytics and automated learning, that are aimed at reducing the costs associated with the elaboration of large datasets (Swanson *et al*., 2015).

From this standpoint, citizen science has been sometimes understood as a low-cost approach to large-scale scientific research (Steininger *et al*., 2015), permitting to save from half to three quarters of the resources absorbed by traditional modes of scientific knowledge generation (Kaartinen *et al*., 2013). However, the design and the implementation of citizen science projects does not come without charges. Overlooking this may lead to an opportunistic view of citizen science, which prevents research institutions from fully benefitting from citizen scientists' contribution (van Strien *et al*., 2013).

Citizens may lack the skills and expertise to perform scientific activities. Hence, there is the risk that their involvement in data collection is affected by misclassifications of evidence and false positives (Miller *et al*., 2013). This is harmful to the advancement of scientific knowledge, producing overestimations and lack of grasping of investigated phenomena (Pillay *et al*., 2014). False negative errors are common in citizen science, too. Citizens may fall short in detecting complex data and to report them (Ruiz-Gutierrez *et al*., 2016). If not acknowledged and addressed, false positives and false negatives endanger the expert scientists' ability to use data contributed by citizens (Swanson *et al*., 2016), depleting the latter's actions (Santangeli *et al*., 2015).

Organizational actions are required to minimize the citizens' improper contribution to scientific research and to address the *cons* of citizen science. The introduction of specialized organizational units to coordinate citizens' involvement and the design of organizational precautions accounting for the misalignment between expert scientists' expectations and citizens' contribution are especially relevant for this purpose (Altwegg and Nichols, 2019). Since these organizational efforts involve additional costs, an expansion of the size of citizen science projects is required to make them cost-effective and to avoid backlash on the economic sustainability of research institutions (Heigl *et al*., 2017).

The purple cluster: enhancing the reliability of citizen science

One of the most challenging issues related to participatory research concerns the integrity of data contributed by citizen scientists. Whilst citizen science may trigger gains in terms of speed and size of data collection and classification (Zapponi *et al*., 2017), limited endurance of patience, the desire to rapidly accomplish tasks, inadequate expertise, and lack of experience may endanger the trustworthiness of citizens' contribution (Bodilis *et al*., 2014; Goczal *et al*., 2017). The problems of data consistency and reliability are particularly recurring when extraordinary or rare phenomena are being investigated, which put the ability of citizen scientists to collect and report scientific information under stress (Cox *et al*., 2012).

Literature maintains that a tripartite – methodological, technological, and motivational – approach is needed to improve the dependability of citizen scientists' involvement in scientific research. From a methodological perspective, citizen science should not be conceived of as an independent research approach; rather, it should be envisaged as a complementary tool to conventional research models which is aimed at increasing the coverage of data collection and processing (Hadj-Hammou *et al*., 2017). The combination of participatory science and conventional research is intended to shed lights into the micro-level attributes of the phenomenon being investigated, permitting to better assess the reliability of citizen scientists' contributions (Ries and Mullen, 2008).

Two technological ingredients should be included in the recipe for reliable citizen science. On the one hand, robust tests fed by big data analytics permit to check the consistency of data delivered by citizen scientists (Bois *et al*., 2011). On the other hand, web-based platforms increase the opportunities of exchanges between expert scientists and citizens, establishing a virtual platform to train the latter (Vermeiren *et al*., 2016). Providing citizen scientists with tailored educational activities serves a twofold purpose: it enhances the citizens' skills and competences, and it nurtures their self-efficacy (Delaney *et al*., 2008). Finally, yet importantly, acknowledging the societal relevance of scientific issues and the impacts produced by citizen science projects is useful to encourage citizen scientists' active and durable participation in scientific research, motivating them and nourishing their commitment to scientific knowledge co-production (Scyphers *et al*., 2015).

The cyan cluster: ensuring the retention of citizen scientists

Citizen scientists' retention is one of the key success factors of citizen science projects (Taylor *et al*., 2019). Scholars have proposed a wide array of strategies that are aimed at building loyalty and trust between expert scientists and citizens for the purpose of long-term retention. Such strategies concern both the citizen scientists' role identity and their willingness to establish a co-creating partnership with expert scientists. Actually, citizen scientists' retention and active engagement in participatory science rely on the ability to elicit the distinguishing needs of citizen scientists and to encourage a tailored dialogue between them and expert scientists. However, attention should be paid to the specific categories of people involved in scientific knowledge co-production.

Whilst amateurs and occasional citizen scientists are primarily interested in the opportunity to merge recreational aims to their contribution to research activities (Alessi *et al*., 2019), advanced-level citizen scientists adhere to a philosophy of equity, trust and learning (Huddart *et al*., 2016). More specifically, they look at the impact of citizen science to the enhancement of their personal skills and, therefore, to their cultural (and professional) growth (Ryan *et al*., 2016). Loyalty and fairness are especially relevant to engage advanced-level citizen scientists in knowledge co-production. The construction of relationships based on trust requires the explicit acknowledgement of citizen scientists as partners of expert scientists. This is possible by providing citizens with the technologies and tools enabling them to participate in data collection and/or classification, by addressing the difficulties they face in accomplishing their research tasks, and by actively involving them in knowledge dissemination (De Coster *et al*., 2015; Newson *et al*., 2015).

Discussion

Citizen science triggers a new mode of scientific knowledge production which is rooted on science democratization. Citizens' involvement enacts a distributed approach to scientific research, according to which expert scientists are called to act as enablers of citizen scientists, empowering the latter to support research institutions in the construction of comprehensive datasets and in processing huge amounts of data. However, literature quarrels in understanding citizen science either as a cost-effective way of gathering massive datasets or as a democratic approach to scientific research aimed at bridging the intellectual divide between expert scientists and the community.

Despite the multifacetedness of citizens' involvement in large scale research projects, this literature review revealed several commonalities in the approaches to citizen science, which allow us to propose a polarization of initiatives intended to engage people in scientific activities. As graphically depicted in Figure 4, large-scale citizen science projects can be located within a continuum consisting of two extremes. On the one hand, a "contributory" mode primarily serves the research institutions' demands. Citizens are involved in basic, time-consuming research activities, such as data collection and transcription. They perform as junior partners of expert scientists, being not directly involved in a co-creating effort aimed at knowledge co-production. The engagement of citizen scientists is primarily targeted to releasing expert scientists from repetitive and low value-added tasks, thus increasing the capabilities of research institutions without generating additional costs. Gamification, targeted incentives, and compelling protocols are required to address citizens' involvement in data collection, classification, and processing and to foster the integration of their contributions with the activities accomplished by expert scientists. On the other hand, an "open science" mode is addressed to the citizens' active engagement in the co-design and co-delivery of research activities, in a perspective of knowledge co-production. Citizens are conceived of as peers of expert scientists, acting as relevant knots of the knowledge ecosystem enacted by research institutions. Since poor motivation, limited skills, and inadequate awareness may hinder the citizens' engagement in an "open science" approach to citizen science, expert scientists should embrace an empowering role, which is aimed at enabling citizens and encouraging their durable participation in scientific research.

[Please, insert Figure 4 about here]

As shown in Figure 5, the “contributory” and the “open science” approaches to large-scale citizen science require different steps to be implemented. The design of “contributory” citizen science can be depicted as a linear process, whilst “open science” sticks to a circular, iterative process. Involving citizens as relievers of expert scientists usually kicks off with the arrangement of ICT-based solutions – such as web-based portals – that work the point of contact between expert scientists and citizen scientists; furthermore, they host the virtual context in which citizen scientists accomplish their tasks. Next, a communication campaign is launched to attract lay people and to make them aware of the opportunity to contribute to scientific research. The arrangement of a clear and consistent research protocols follows: expert scientists define instructions and guidelines formalizing the expected contribution of citizen scientists. In most of the cases, citizens have to complete a brief training, which provides them with the knowledge and the basic skills to accomplish their tasks. As previously anticipated, citizen scientists’ contribution is fully mediated by IT tools: whilst they foster the effectiveness of participatory research, they also create a virtual barrier between citizens and expert scientists, which undermine the establishment of a co-creating dialogue between them. Usually, machine learning algorithms are embedded in IT platforms, which are intended to train automated data processing technologies and to check the reliability of citizen scientists’ inputs. A short-termism characterizes the participation of citizens to “contributory” citizen science.

[Please, insert Figure 5 about here]

Large-scale citizen science projects inspired by an “open science” perspective are initiated with tailored educational activities, which have a threefold purpose. Firstly, they improve the citizens’ understanding of the scientific issues that are related to the citizen science project. Secondly, they underpin the citizens’ awareness of their contribution to the advancement of scientific knowledge. Thirdly, they foster the establishment of a co-creating partnership between expert scientists and citizens. Far from involving large groups of citizen scientists, “open science” usually targets small groups of contributors. These groups are coordinated by one or more expert scientists, who act as research institutions’ boundary spanners and as a landmark point for citizens. The design of protocols and guidelines is steered by expert scientists, but citizens are involved in the process. IT tools and web-based platforms are exploited as enabling instruments, providing citizen scientists with the information and the feedback they need to perform their research activities effectively. If needed, citizens can borrow technologies and tools to participate in scientific research from the research institution which coordinates the citizen science initiative. Projects embracing an “open science” view are generally not terminated at the end of data collection and or data processing; rather, the finalization of research activities triggers a further step of education, which may initiate a new round of citizens’ involvement in scientific research.

These two ideal approaches to large-scale citizen science have diverging impacts. Whilst the “contributory” mode has immediate positive implications for research institutions, which benefit from the opportunity to enhance their research capabilities without affording additional costs, it may have drawback on the public understanding of science. More specifically, the "contributory" approach basically encapsulates a short-term involvement of citizen scientists in research activities. Therefore, it partially contributes to democratizing scientific knowledge and has limited effects on the enhancement of individual and collective awareness of scientific issues being investigated. In sum, contributory citizen science tries to expedite the expert scientists' ability to collect and process huge amount of data. Besides, it intends to increase the research institutions' institutional legitimation, by establishing a bridge with the community. However, the "contributory" mode does not enable citizens to actively participate in co-designing and co-implementing research activities, thus generating a rhetoric of involvement triggering limited engagement and poor commitment. Gamification and awards are generally used as motivating tools to sustain citizen scientists' involvement and retention in contributory citizen science. However, such solutions are not effective in paving the way for a real democratization of science.

The "open science" approach to large-scale citizen science has both direct implications for the advancement of research institutions' capabilities and social spill-overs. Empowering citizens and actively engaging them in the different stages of scientific research is essential to broaden the public understanding of science. Also, it ensures fairness in the implementation of participatory science, allowing citizen scientists to act as peers – rather than as subordinates – of expert scientists. Thirdly, it creates a direct link between science and people, which is key to inspire better policy making. This permits to immediately benefit from advancements in science due to informed decision making at the macro and micro levels. Lastly, it generates greater opportunities for scientific progress, contextualizing scientific knowledge to every-day life circumstances.

Several limitations affected this study: acknowledging such shortcomings allows us to better contextualize the original contribution of this literature review. The breadth of this study was constrained by the use of only one citation database to collect scientific items. However, indexing more than 21,000 peer-reviewed scholarly journals published worldwide in over 250 disciplines, Web of Science provided us with a comprehensive snapshot of the state of the art in the field of large-scale citizen science. Moreover, the focus on large-scale scientific research does not allow us to generalize the research findings to the whole universe of initiatives aimed at promoting participatory research. Thirdly, the narrative approach employed to systematize the research items may have influenced the findings' report with subjective biases. Nevertheless, it ensured a unique and comprehensive presentation of the study findings, illuminating the distinguishing attributes of large-scale citizen science. Lastly, only peer-reviewed articles were included in the basket of this literature review. Whilst this decision increased the robustness and the dependability of the study results, it restricted the scope of our research.

Conclusions and future perspectives

Citizen science enacts a new way of accomplishing large-scale scientific research. Whilst engaging citizens in scientific research fosters the democratization of science, not all participatory practices are effective in acknowledging a scientific citizenship to people. When a contributory approach is undertaken, citizen scientists are primarily involved in performing simple and repetitive tasks, which are intended to increase research institutions' capabilities and to save time and resources of expert scientists.

Literature has warned that “contributory” large-scale citizen science projects may lead to short-termism in the design of participatory practices. If not boosted through incentives, rewards, and motivation, involving citizen scientists in accomplishing basic tasks creates disengagement and does not sustain their durable participation in scientific endeavours. From this point of view, the need for achieving a democratization of science solicits a transition towards an “open science” approach to large-scale citizen science projects. Making citizens active co-producers of research activities advances the public understanding of science through direct participation, facilitating the achievement of a scientific citizenship.

Further developments are needed to push forward what we currently know about large-scale citizen science. *Inter alia*, greater attention should be paid to the “grey” side of participatory approaches. Although it has been largely argued that a “contributory” approach to large-scale research entails gains in the efficiency of research endeavours, it should be acknowledged that inadequate efforts to address the problems of misalignment between expert scientists and citizen may prevent the use of data contributed by the latter. This may endanger the relationship between expert scientists and citizens, implying the failure of large-scale citizen science projects. Advancements are also required to gauge – both in terms of quantity and quality – the manifold implications that are triggered by the engagement of citizens in accomplishing large-scale scientific research. This is especially true when an “open science” approach is taken, which has multiple social spill-overs at the individual and collective levels. Last, but not least, future studies should shed light on the hard and soft requisites to the design large-scale citizen science projects that are consistent with an “open science” perspective. More specifically, evidence is needed to illuminate the role that citizens may have in co-producing knowledge with expert scientists and to increase the collective awareness of the contribution of participatory research to advancing scientific research.

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