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A review of Citizen Science within the Earth Sciences: potential benefits and obstacles

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ABSTRACT

The field of citizen science is a rapidly evolving type of scientific research focussing on the collaboration of motivated volunteers (citizen scientists) with professional scientists to generate new knowledge and information. In recent years, there has been a steady growth of Earth Science related citizen science projects that aim to build knowledge, awareness and ultimately resilience to key local- to global-scale environmental issues (*e.g.*, geohazards, environmental monitoring). In addition, there has also been progression from small pilot studies to large data collection Earth Science citizen science initiatives that are used to underpin modelling. However, despite this, numerous operational and strategic challenges exist and whilst the awareness of citizen science has improved markedly, it is clear that the direct impact of citizen science on policy and decision making is still limited. Within this paper, we review these challenges alongside defining citizen science itself, and its benefits. The range of methods and applications of citizen science are explored through a series of case studies centred on geohazards, observations & classification, multi-topic, and education/outreach. The paper also explores future citizen science opportunities within Earth Science.

Contents

1. Introduction

Citizen science is the participation of non-professional scientists within scientific research helping to generate new knowledge and information (Gura, 2013; Bonney et al., 2014). The past decade has seen a massive growth in the number of citizen science

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activities and participant volunteers (McKinley et al., 2015; Kosmala et al., 2016). This growth reflects a number of phenomena: (1) the demand to make research societally relevant (Cohn, 2008); (2) to develop large-scale and long-term monitoring datasets to underpin science and planning decisions (Conrad and Hilchey, 2011); (3) an increased public awareness of environmental issues; and (4) the 'enabling' of both technology, (*e.g.*, low cost sensor networks, smartphones) and citizen scientists (Buytaert et al., 2014). There has also been a fundamental shift in the style of activities from broad top-down activities to participatory, community-based bottom-up activities where participants and professional scientists interact (Paul et al., 2018). Accordingly, citizen science is fast being recognised as a scientific approach with global potential with the ability to involve local community groups in tackling large global challenges (Pocock et al., 2019).

Historically, the application of citizen science is well established within the fields of conservation and environmental monitoring (Huddart et al., 2016; Bonney et al., 2014, 2016; Kosmala et al., 2016, Kullenberg and Kasperowski, 2016.). There has also been a steady growth in the application of citizen science to Earth Science, particularly within geohazard research, monitoring and characterisation (Paul et al., 2018; Cieslik et al., 2019; See, 2019). Its aim has been to influence decision-making, policies and ultimately contribute towards understanding key global environmental and social issues such as progress towards the United Nations Sustainable Development Goals. The purpose of this paper is to provide a review of citizen science within the Earth Sciences, identifying the key benefits and challenges – both strategic and operational, that face the citizen science community. We provide examples of citizen science activities within geohazards, monitoring and characterisation, and education and outreach and consider emerging opportunities within citizen science.

2. Citizen Science: evolution, benefits and challenges

2.1. What is Citizen Science?

The citizen science concept encompasses scientific activities that utilise volunteer 'citizen scientists' for the purposes of some or all of the following - research design, data collection, data analysis and science dissemination (Cohn, 2008; Silvertown, 2009; Haklay, 2013; Bonney et al., 2014; Paul et al., 2018; Doyle et al., 2019). This broad concept of citizen science is well established, however numerous variations in definition (and terminology) exist and these often have subtle differences in meaning and application (Buytaert et al., 2014). True citizen science projects can be distinguished from more general projects that engage with public and stakeholders by the relative level of volunteer participation, which is influenced by one or more motivational factors (Paul et al., 2018). Haklay (2013), for example, defines four levels of citizen science participation from 'crowdsourcing' (Level 1, low) through to 'extreme citizen science' (Level 4, high). Under this typology, successive participatory levels record the progression from primary data gathering (*i.e.*, Level 1) though to fully collaborative (with professional scientists) research involvement which may include defining the research question and scope, data collection and data analysis (Level 4).

Considerable debate has also focussed on the terms used to describe 'participants' of citizen science. Oberle et al. (2019), for example, have questioned the ethical use of the term 'participant' especially if individuals are not aware (or understand) how their data is being used. Whilst this study focusses on the role of 'participants' within the field of medical science it has clear crossover into other forms of participatory science. Paul et al. (2018) argues, that a participant can only be called a 'citizen scientist' when they actively volunteer – being motivated by one or more factors, and maintain their activity and contact with professional scientists throughout the entire project duration. This definition highlights several key factors, most critically that participatory engagement is 'voluntary', 'motivated' and 'maintained' throughout the project. Other literature employs terms to describe participants including 'non-professional' and 'amateur' although these can have somewhat negative connotations implying that the science is sub-standard, or undertaken by an unqualified non-specialist or is not effectively quality controlled (Torrens, 2006; Noè et al., 2019). Participants of citizen science projects are now commonly referred to as 'citizen scientists' or 'volunteers' and it is also relevant to highlight the distinction between 'direct citizen science' - where data is studied without verification and 'verified citizen science' – where only contributed data that has been verified by an expert is utilised (Gardiner et al., 2012).

Whilst citizen science under its modern guise is a very recent concept, the role of clearly motivated, volunteer citizen scientists and their collaboration with 'professional scientists' has been noted as far back as the 1700s (Raddick et al., 2009). Within Earth Science, fossil collections collated by citizen scientists have proven to be of great importance in the fields of paleontology (Leigh Star and Griesemer, 1989; Torrens, 2006). Fossil collectors such as Mary Anning, Alfred Nicholson Leeds and Steve Etches are three individuals who have collected fossils from the Jurassic Coast and the Lower Oxford Clay building internationally-significant fossil collections (Noè et al., 2019). Their ongoing legacy is an enhanced understanding of ancient marine and terrestrial ecosystems (Noè et al., 2019) and the recognition of the Jurassic Coast as a UNESCO World Heritage Site (Larwood, 2019). In some cases, it has been known that the citizen scientist has become the leading scientist. For example, John Hannes Callomon, a professional chemist, specialising in high-resolution molecular spectroscopy, discovered ammonite sexual dimorphism and became an international expert on the stratigraphy of the Middle and Upper Jurassic (Cope, 2016). Within the field of paleoclimatology, James Croll was a self-taught nineteenth century citizen scientist who linked astrophysics to climatology and the cyclic development of ice ages (Bol'shakov et al., 2012). Pearce (2018) described Croll as the "...janitor who unlocked the secret of how ice ages happen...". Some have debated whether these contributions can be classified as citizen science in the true modern sense (Pearce, 2018; Noè et al., 2019). These individuals were clearly volunteers and highly-motivated, however research was often not undertaken under the guise of a formally-defined project. In addition, whilst all of the aforementioned citizen scientists engaged with the broader scientific community, their level of expertise and scientific contribution by some was perhaps not always acknowledged by leading 'professional' scientists of the time (Pearce, 2018; Noè et al., 2019).

In recent years, there has been a marked increase in the number of active citizen science projects and participating citizen scientists (McKinley et al., 2015). Citizen science projects have also seen a notable switch in emphasis from volunteers simply collecting data, to more active involvement through data analysis and interpretation phases of the research process (Buytaert et al., 2014; Huddart et al., 2016; Paul et al., 2018). This reflects several significant developments: (1) technological 'enabling' including the cost and access to mobile technologies, the internet and low-cost sensor networks which has made citizen scientist participation, data analysis and science dissemination easier (Newman et al., 2012; Buytaert et al., 2014); (2) the substantial reduction of science research funding; (3) the requirement of large-scale and long-term monitoring datasets to support effective planning and decision making (Conrad and Hilchey, 2011; Doyle et al., 2019); (4) the growing public awareness and interest in environmental science, global issues and related educational and outreach activities

(Bonney et al., 2009; Silvertown, 2009); and (5) the empowerment of citizen scientists to contribute to projects once considered the realm of professional scientists through the 'voice' of social media, blogs and online encyclopaedias (*e.g.*, Wikipedia) coupled with the accessibility of new technology (Rossiter et al., 2015). Much of the recent growth in citizen science projects has focused on environmental (ecological) monitoring and conservation where it has made a significant impact (Roy et al., 2012). Specific projects have contributed significantly to increased ecological and environmental knowledge at various spatial and temporal scales (Dickinson et al., 2010; Bonney et al., 2014; McKinley et al., 2015).

2.2. Crowdsourcing

As outlined previously, the terminology used in different citizen science projects is continuing to evolve but has also become increasingly interchanged and confusing. The term 'crowdsourcing' is a widely-employed and popularised term that is often used (and mis-used) within the context of citizen science projects. In very general terms it refers to " . . . the activity of giving tasks to a large group of people or to the general public, for example, by asking for help on the internet . . . " (Cambridge Online Dictionary, 2019). From a citizen science perspective, the term 'crowdsourcing' is often used within the context of the mass acquisition of data or information. It therefore represents the lowest level of participant engagement with data analysis, interpretation and dissemination undertaken by professional scientists (Haklay, 2013; Paul et al., 2018).

There are a number of types of crowdsourcing that can be used depending on user needs and the needs of the project, and these reflect different levels of participation (Table 1). *Public crowds* (Level 1) are the most commonly-used type of crowdsourcing being an easily accessible, cost-effective method for gathering large amounts of data, especially over a large spatial area, in a relatively short space of time. There are many examples of public crowdsourcing in the Earth Sciences including the United States Geological Survey's (USGS) 'Did you feel it?' earthquake app. In some instances, the 'crowd' may be specialist and/or authoritative having positive implications on data validation requirements. The *expert crowd* (Levels 2-3) crowdsourcing method involves targeting a specific pool of citizen scientists to source data. For example, 'FINTAN' is an Ordnance Survey (OS) crowdsourced gazetteer of 'local' names and places, and used by the UK Maritime Coast Guard Agency to improve rescue efficiencies. For crowdsourcing and more generally volunteered geographic information (VGI), participation can be described as *active* or *passive* and relates to whether a participant is consciously (active) or passively collecting data. The Waze navigation app collects both real-time travel (passive) data, whilst maps can also be updated by user submitted fixes (active). Normally crowdsourcing has a specific purpose and is collaborative and *co-designed* with individuals working together to form a specific outcome (e.g. OpenStreetMap). Many forms of crowdsourcing require user registration whereby citizens register and login as a user. This has benefits such as the ability to assess user activity over time, confidence, and the ability to attract citizens who are interested and engaged in a subject. However, it could also have the opposite effect and deter citizens who do not want to share personal details or register.

2.3. Benefits and Challenges of Citizen Science

The primary benefits of citizen science relative to traditional science reflect the complex balance of cost, quality and quantity of data, and the speed that the science outcomes are disseminated (Gardiner et al., 2012). The cost of undertaking citizen science relative to traditional science is a key consideration due to recent reductions in research funding coupled to the resources required to resolve key research questions. In simple terms, the cost of citizen science is typically lower than traditional science because the former has the potential to utilise an underused (often unpaid) labour resource at a relatively low cost. The financial value of the citizen science contribution has been examined by several studies. Sauermann and Franzoni (2015) compared the value of unpaid 'citizen' contributions to counterfactual costs from traditional paid labour sources on seven projects. Their study demonstrated that the financial contribution of citizen scientists to projects was generally significant but did vary both between and within (temporally) projects. Frequently, this reflected the level of citizen participation, which typically declined during the lifecycle of the project with temporary increases triggered by marketing campaigns. Theobald et al. (2015) attempted to quantify the financial value of citizen scientists to biodiversity-related citizen science projects. They demonstrated that annually, US $2.5 billion of in-kind value was provided by citizen scientists but acknowledged that this figure was likely to be a significant under-estimate because only 12% of projects disclosed the level of volunteer contribution. Another study identified that a citizen science program (directed) can generate 3-4 times the number of samples generated by traditional research for the same cost (Gardiner et al., 2012). Further factors contribute to the overall cost of a citizen science project and these include whether training is provided to citizens (*e.g.*, the CITIZAN project, Sherman, 2015) or whether experts are utilised to provide quality assurance to data and observations (Gardiner et al., 2012). Another key benefit of citizen science is its more outwards-facing aspect. Citizen science by its very nature promotes education, public engagement and outreach

Table 1
Example levels of participation in crowdsourcing.

	Level	Participation	Example
Public crowd	Level 1	Mass data collection, no expert knowledge needed. Rapid data collection, low cost Public crowds Citizens contribute, non-specialists Active or passive	Generating maps of occurrences e.g. earthquakes, volcanoes, GeoSocial.
Expert crowd	Level 2	Specific knowledge needed, targeted crowd Specialist crowds, Citizens are more focused/ informed Active	Registration and basic training might be provided, using specific professionals or students *e.g.*,James Madison University, Ireland
	Level 3	Data processing/ analysis Citizens are considered as interpreters or provide problem definition Active Co-design	Input and potentially processing is required, sometimes rewards offered *e.g.*, Goldcorp, i-Mars, OpenStreetMap, Cobweb project.

(Bonney et al., 2009; Dickinson et al., 2012). It can also promote a greater awareness of the local and wider environment (Haywood, 2014) and an increased understanding of relevant environmental issues (Resnik et al., 2015). Citizen science can also provide a valuable social benefit, empowering people and providing them with a voice, creating a sense of community and promoting learning (Danielsen et al., 2005). Arguably, the key benefit of citizen science is the ability to generate and acquire key data and knowledge with some citizen contributions to projects approaching 50% of the total dataset (Cooper et al., 2014). This typically encompasses newly-acquired data and information gathered either opportunistically or following a specific workflow, through the interpretation of pre-existing data, tacit knowledge or the submission of samples to professional scientists for analysis.

Despite the obvious benefits, there are significant challenges that face citizen science and these can be grouped broadly under the themes of strategic and operational challenges. From the strategic perspective, it has been argued that the overall impact of citizen science activities has proven to be somewhat limited (Irwin, 2018). Irwin (2018) has argued that this is because many projects are too short-lived and aren't fully integrated with more conventional science approaches in a way that more effectively informs policy and decision making. Whilst this may in-part reflect operational issues, it could also highlight a perception by some scientists that citizen science is not mainstream science and that several issues (e.g. quality, motivation of participants) undermine its reliability (Theobald et al., 2015). A second strategic challenge is that whilst citizen science has immense global potential (Pocock et al., 2017), recent surveys of environmental citizen science activities show a strong spatial bias towards 'western' developed countries with, by comparison, the visibility of activities in lower income countries far more limited (Bonney et al., 2014; Theobald et al., 2015; Chandler et al., 2017; Pocock et al., 2017, 2019). An assessment of the Earth Science literature (see Section 3) paints a similar picture although it is clear the potential that citizen science offers is well recognised (Cieslik et al., 2019; Shah et al., 2018; Navakanesh et al., 2019). The reasons behind this spatial pattern are complex. In the first instance, Haklay (2013) considered volunteering in western developed countries to be much more common and considered by many to be a serious leisure activity partly reflecting cultural views on volunteering. In a recent study, Pocock et al. (2017) utilised a focus group to assess the barriers to citizen science for environmental projects in East Africa. Their study found that barriers principally correspond to people / institutions (*e.g.*, organisational capacity, awareness, perceived value of data) and structure (*e.g.*, access to technology, literacy of participants, language, uneven spatial distribution of participants). Therefore, for a citizen science activity to be successful, Loos et al. (2015) argued that it is imperative to consider the social, cultural and technological context of the activity, although this varies across the world and within countries depending on demographics, location (*i.e.*, urban or rural), income level and language (Haklay, 2013). Building and maintaining an effective Citizen Science project should, according to Rossiter, et al. (2015) consider five key factors: (1) Identification of the type of data that can realistically be provided by a non-specialist and identification of the appropriate citizen groups that would be in a position to provide these; (2) a streamlined process that enables the volunteer to quickly collect data without the need for detailed training, registration processes, etc.; (3) a strong publicity campaign via a number a relevant channels and perhaps training opportunities; (4) protocols for data collection and submission by the citizens (*e.g.*, Gardiner et al., 2012); (5) a clear reward/benefit scheme.

Citizen science can also suffer from numerous operational challenges linked to project roll-out, visibility, recruitment/retention and communication and these can create significant project bottlenecks and sustainability issues. Understanding participant motivation is arguably one of the most significant challenges for a citizen science project but is essential in-order to recruit participants, ensure buy-in and retain involvement (Geoghegan et al., 2016; West and Pateman, 2016). However, participant motivation is a highly complex issue (Buytaert et al., 2014), reflecting a variable combination of intrinsic (*e.g.*, scientific curiosity, sharing knowledge, social and environmental concerns, values) and extrinsic (*e.g.*, career) factors (Finkelstein, 2009; West and Pateman, 2016). Interestingly, there is little published literature available on what motivates people to participate in citizen science projects (Geoghegan et al., 2016), however there are many published studies focussing on environmental volunteering which are in-part analogous (West and Pateman, 2016). Initial and ongoing participation in a citizen science project will ultimately depend upon an individual's motivation combined with whether an opportunity fits in with their everyday lives, which in-turn reflects a variable combination of an individuals' personal attributes, values, circumstances and demographic (West and Pateman, 2016). Some have questioned the broader motivation (e.g. conflicts of interest) and commitment of citizen scientists (Show, 2015). For example, Sauermann and Franzoni (2015) reported that the majority of citizen scientists participated only once to a citizen science project with regular contributors being the minority. Their research also showed that top contributors input higher levels of effort, but that often related to speed, which developed over multiple sessions implying learning rather than differences in skills. Providing incentives or rewards can lead to improved participation, but financial incentives can lead to unrealistic participant expectations and can undermine the sustainability of a project.

Other concerns have been raised over data quality (Alabri and Hunter, 2010) and fears that poor-quality data may be underpinning science, policy and decision-making (Cohn, 2008; Dickinson et al., 2010). For example, how can the robustness of citizen observations be assessed, and how can you combine precise and imprecise observations? These concerns have been raised because citizen scientists may not have had training in scientific data collection, data management and research integrity so systematic errors could occur impacting data quality (Resnik et al., 2015). Whilst there are several examples where errors have been identified within citizen-collected datasets (*e.g.*, Bonney et al., 2009; Dickinson et al., 2010; Gardener et al., 2012), the sources of errors and bias are very similar to those encountered within professionally-sourced data and can include non-random observations, non-standardised data capture, under-detection and miss-identification (Shamoo and Resnik, 2015; Kosmala et al., 2016). Numerous studies have shown that data quality within citizen science projects can be measured and enhanced by taking a more 'direct citizen science' approach with easily achievable tasks, rigorous data collection, testing and management workflows (Dickinson et al., 2010; Crall et al., 2011; Gardiner et al., 2012; Kosmala et al., 2016). For example, Kosmala et al. (2016) identified seven procedures that could enhance data quality within a citizen science project, including: (1) iterative task development and tool design; (2) citizen training and testing; (3) use of standardised and calibrated equipment; (4) expert validation; (5) replication and calibration across citizen scientists; (6) skills-based statistical weighting of volunteer classifications; and (7) accounting for random error and statistical bias.

Significant ethical challenges occur within citizen science and these include matters relating to exploitation, data ownership, data sharing and conflicts of interest (Rasmussen and Cooper, 2019). *Exploitation* in citizen science can occur because citizen scientists are providing their time and information without the expectation of financial compensation (Riesch and Potter, 2014). It can involve one or a combination of a lack of consent, harm and inequality (Resnik et al., 2015). Common examples of exploitation include the misleading of citizen scientists about their role in a particular project or the purpose of the project, and formal acknowledgment of the contribution of citizen scientists. The latter is a particular problem within citizen science projects, because citizen scientist involvement is often only declared in the minority of projects and frequently hidden within appendices or supplementary information (Cooper et al., 2014). This lack of visibility may relate to a perception that scientific contributions from citizen science are worth less than their educational value and this has made it challenging for scientists to secure research grants on

Table 2
Summary of examples and Citizen Science categories observed in this review.

Category	Theme	Project name	Citizen type	Registration	Organisation
Hazards	Earthquakes	MyShake	Passive, public	Open	University of California
	Earthquakes	Did you feel it	Active, public	Online form	USGS
	Geohazards	GeoSocial	Passive Twitter Public	Social Media harvesting	BGS
	Earthquakes	Taiwan Scientific Earthquake Reporting (TSER) System	Active, public	Unknown	Institute of Earth Sciences Academia Sinica; Seismological Centre, Central Weather Bureau
	Earthquakes	Did you feel it?	Active, expert	Registration	European Seismological Commission
	Earthquakes	Schools seismology project	Active, public	Schools based	BGS
	Landslides	Did you see it?	Active, public	Interactive website	USGS
	Volcanology	Is ash falling?	Active, public	Online form	USGS
	Volcanology	MyVolcano	Active, public, expert	Mobile app	BGS
	Landslides	Report a landslide	Active, public	Web form, email, Twitter	BGS
Observation and Classification	Mapping	i-Mars / Mars in motion	Active, public	Open	Nottingham Geospatial Institute
	Environmental data	COBWEB Citizen OBservatory Web	Active, public	Registration co-design	EA-funded multi-national
	Mineral exploration	Goldcorp Challenge	Active, expert	Registration	Goldcorp
	Stream levels	CrowdWater	Active, public	Open registration	Univeristy of Zurich
	Geology mapping	i-Geology	Active, public / expert	Open Registration	BGS
	Recording temporary rock exposures	GeoExposures	Active, public/ expert	Open Registration	BGS
	Geological photographs from inaccessible places	EXtreme 'EXposures'	Active, public	Registration	
	Identifying coastal change	iCoast	Active, public	Registration	USGS
	River water level readings	Crowd Hydrology/Social water	Active, public	Registration	USGS
	Surface mines, quarries, pits	Britpits	Active, expert	Registration	BGS
Multi-topic	Post-disaster damage assessment	Crowd4Sat	Active, public	Registration	International Institute for Applied Systems Analysis
	Site investigation data	National Geotechnical Database	Active, expert	Registration	BGS
Outreach & Education	Structural field observations	Field mapping course	Active, expert	Students	James Madison University
	Earthquakes	Schools seismology project	Active, public	Schools based	BGS
	Identifying top 50 Quaternary sites in the UK	50th anniversary top 50	Active, public	Open	Quaternary Research Association
	Identifying top 100 geosites	100 Great Geosites in the UK and Ireland	Active, public	Open	Geological Society

citizen science projects (Wiggins and Crowston, 2015). *Data ownership* and *Intellectual Property Rights* (IPR) can present significant challenges to citizen science because they define who owns the data, how it can be used and by whom (Guerrini et al., 2018, Marsnik and Lorentz, 2015, Shamoo and Resnik, 2009). For example, citizen scientists may seek to assert ownership of their contributed data and want to control how the data is both shared and applied by the project. Guidance for IPR is complex and typically, their application can vary between countries. *Data sharing* is at the core of modern scientific research because it promotes critical discussion and enables future studies to build-on completed work (Shamoo and Resnik, 2015). However, this can be compromised by data ownership issues and the premature release of data which can undermine the science and future scientific opportunities (Reisch and Potter, 2014). *Conflicts of Interest* also pose a significant challenge to Citizen Science because they have the potential to introduce bias and undermine public trust (Resnik, 2011; Shamoo and Resnik, 2015). Conflicts of Interest can be finance-related and correspond to financial interests and personal relationships with bodies that fund scientific research (Resnik, 2007). Alternatively, Conflicts of Interest may occur in relation to ongoing legal actions or personal and / or political motivations that citizen scientists may have (Rosen, 2013; Riesch and Potter, 2014).

3. Citizen Science within the Earth Sciences

Citizen science has a strong tradition in the fields of conservation, ecology, water and air quality, and biodiversity, however, this is beginning to evolve and broaden across other disciplines. More recently, citizen science and crowdsourcing are being used within many different domains in Earth Science, particularly geophysics, monitoring (*e.g.*, volcanoes and stream levels) and geohazards including flooding, landslides, earthquakes. Several examples of the application of citizen science within the field of Earth Sciences are provided below and arranged into four themes: GeoHazards, Observations & Classification, Multi-topic, and Education/outreach. These examples have been selected as being representation of citizen science in the broadest sense but are not intended to be a fully inclusive list, there are a multitude of other projects and readers are encouraged to look up the project webpages many of which list additional references. A summary is provided in Table 2 and a webpage reference list is provided for further information.

3.1. Geohazards

The geohazards theme has seen a rapid increase in the use of citizen science-type project and many of these are centred on the field of earthquakes. For example, the United States Geological Survey's (USGS) 'Did you feel it?' earthquake app collects information from people who felt an earthquake (Atkinson and Wald, 2007). Researchers then create maps that show people's experiences and the extent of damage (Boatwright and Phillips, 2012). In Europe, another 'Did you feel it?' crowdsourced program is run through a consortium of 36 seismological organisations in 24 countries. This program collects macroseismic data (i.e. earthquake data derived from felt earthquake reports) via online questionnaires or smartphone apps. These independent data sources are being brought together under the auspices of a EuroGeoSurveys working group, the European Seismological Commission (Bossu et al., 2017). Liang et al. (2019) report the development and deployment of a crowdsourced monitoring system in Taiwan. Within this project, participants receive alerts of an earthquake and are encouraged to visit impacted areas and record damage using an integrated mapping platform. Data is then checked and made available publicly and to the wider scientific community. The system was first used during the 2018 Hualien Earthquake (Mw 6.4) and has been highly-effective in raising public awareness and advancing earthquake mitigations.

The three systems examined above are examples of active participation for earthquake geohazards; however, an example of passive participation for geohazard data collection is the use of Twitter as a passive source of crowdsourced information. Twitter is one of the most prominent and widely-used social media platforms with millions of active users who regularly tweet about issues, events and opinions. This makes it a valuable source of information that can be 'scraped' or 'harvested' and analysed, for example to create earthquake maps from social tweets (Bee et al., 2012), or the BGS 'GeoSocial' initiative to gather information relating to geohazards. This passive form of data collection is still in its relative infancy within the Earth Sciences and has advantages (*e.g.*, volume of data generation) and disadvantages (*e.g.*, chaotic data, IPR issues, uncertainty, misused terminology). Web services are also being used to harvest and share information relating to seismic readings within the Schools Seismology Project (Denton, 2008). A form of passive data collection is also employed in the MyShake app, a smartphone application that uses a phone's on-board accelerometers to record local shaking any time of the day or night. The information is collected, analysed and if it fits the vibrational profile of a quake, relayed with the phone's GPS coordinates to the Berkeley Seismological Laboratory in California for analysis (Kong et al., 2016; Rochford et al., 2018).

The application of citizen science to other potential geohazards such as pluvial flooding, landslides and volcanic ash is less visible. (*e.g.*, the USGS's 'Is ash falling' app is a relatively new development). A review article by See (2019) focusses on pluvial flooding (rainfall generated overland flow) and considers how crowdsourcing could contribute to early warning systems and help validate flood forecast models. Most papers reviewed in this study were dated 2014 or later suggesting an emerging area of research although examples provided were not always specific to pluvial flooding. Their conclusions highlighted that results were more beneficial when sourced through specific applications rather than through passive data mining (*e.g.*, through Twitter). Cieslik et al. (2019) presents the preliminary results of a research project in Nepal focussing on landslide geohazards, which includes a citizen science component. The study highlights the importance of citizen science activities and the potential it has to build local knowledge that will enabling communities to more effectively adapt to change. The study also develops a conceptual typology for multi-levelled participation, distinguishing between community science, participatory environmental modelling and virtual citizen science providing examples of how these approaches can benefit stakeholders. 'Did you see it?' and 'Report a Landslide' are interactive websites by the USGS and the British Geological Survey (BGS) that crowdsource information on landslides. Other BGS citizen science projects include submitting geology photos from difficult to reach terrain (EXposures), using smart-phone apps to collect data on soils (*my*Soil) or samples of volcanic ash (*my*Volcano). For many of these, users do not need to be experts but they are requested to register in order to submit information.

3.2. Observation and Classification

A large proportion of citizen science projects used within the Earth Sciences are aimed at collecting large amounts of baseline observational data. In order to achieve this, platforms that enable professional scientists to access citizen scientists have been created. The Zooniverse project is a citizen science platform with well over 1 million citizen scientists contributing to multiple projects divided into themes from biology and medicine to climate and space science. Researchers at the Nottingham Geospatial

Institute presented findings for the i-Mars project (Geological changes observed from satellite imagery) at the European Geological Congress (EGU) in 2015. The 'Mars in motion' citizen science platform was created through the Zooniverse framework and asks citizen scientists to identify changes on Mars' surface. It is designed to work alongside data mining techniques on data provided from ESA (European Space Agency) missions, bringing together expertise across Europe. An i-Mars web GIS is available, however, it is unclear what results came from the crowdsourcing project and it is no longer in operation.

Much of the professional crowdsourced data, certainly within the earth sciences, has traditionally been captured offline. This is increasingly being migrated to a digital workflow through utilisation of a digital ingestion pipeline and data deposit portal such as that being used by the British Geological Survey. This means that where possible, web services are used to capture data (*e.g.*, Web Map Services) enabling the capture of associated metadata and therefore more detailed/useful information. A key example is the use of specialist geotechnical data provided in industry standard formats (Association of Geotechnical and Geo-environmental Specialists (AGS)) directly into the BGS repository and then made openly available online.

There is an additional element of co-design within some projects, for example, the COBWEB project (Citizen OBservatory Web). This project involved citizen scientists in five European countries (UK, Ireland, Netherlands, Greece and Germany) collecting environmental data using mobile devices and incorporates an element of citizen scientist co-design where local community groups could run projects and contribute to the pilot data collection, development, and improvement of COBWEB. An important part of the project was to address the issues of having large volumes of crowdsourced data in individual silos. They proposed solutions for the development of mobile applications, which generate data compliant with open interoperability standards and facilitate integration with Spatial Data Infrastructures (Higgins et al., 2016).

One example of a crowdsource monitoring project is CrowdWater. CrowdWater is a project that aims to monitor river levels in Swiss rivers to help improve the forecasting of extreme hydrological events such as flooding or droughts. Registration to open to everyone who can collect measurements using a smartphone app that creates a 'virtual measuring station'. Data is uploaded to the CrowdWater website and published anonymously. A review of the initial findings was published by Seibert et al. (2019) who identified the enormous value of the data but also highlighted possible sources of error often associated with placement of the virtual stream gauge.

Arguably one of the most well-known crowdsourcing projects within the earth sciences, specifically mineral exploration, was the Goldcorp Challenge in 2000/2001 (Wilde and Kreuzer, 2016). Essentially, a competition, citizen scientists were given access to all available geological data (a brave choice given that this data was usually highly confidential for exploration companies) for a specific gold mining area in Canada and challenged to identify exploration targets. Goldcorp offered US$ 0.5 M reward and the outcome was hugely successful. It identified new, unknown targets of which more than 80% proved significant reserves, hugely improved exploration times, and created over US$ 6B for the company.

The USGS has a range of observational data collection programmes of citizen science such as the National Map Corps (TNMCorps). This is a large project with citizen scientists (public) successfully editing map structures (hospitals, schools, cemeteries, etc.) in all 50 States, Puerto Rico, and the U.S. Virgin Islands and involves digitisation of analogue map data. The USGS does have other earth science related projects and crowdsource programmes such as iCoast, where citizen scientists identify changes to the coast by comparing aerial photographs taken before and after storms; Crowd Hydrology/Social water, is another very simple easy to use method whereby the citizen scientists read off a water level from a gauge and simply text the measurements. All of this data then feeds into a broad range of scientific research programmes. Citizen scientists are kept up-to-date with online newsletters as well as having the ability to earn rewards such as virtual badges that recognise the efforts contributed.

The BGS has a number of citizen science apps in this category including that for submitting information (text, photos) on temporary rock exposures (GeoExposures) (Powell et al., 2013) (Fig. 1).

'Britpits' is a BGS crowdsourced surface mines, quarries, and pits database, populated from a range of providers in the private and public sector including Local Authorities, OS Maps, BGS field slips, and companies working the ground. The dataset is used for minerals research, environmental impact assessment and other purposes. The BGS's main crowdsourcing platform is their i-geology app (Fig. 2), which provides 1:50 000 scale geology map data with additional functionality where users can easily submit comments and upload photographs and data. The app aims to gather new information to help improve BGS Digital Geological mapping. There is a large community of professional, student and citizen scientist geologists, as well as members of the public, who use the geological map for work and pleasure. Feedback is encouraged and regularly received.

3.3. Multi-topic

Whilst many projects seek data for specific subjects or themes, there are some that are broader in scope and collect information covering a variety of topics. The Geo-wiki Project, led by the International Institute for Applied Systems Analysis (IIASA) has looked at a range of issues globally including flood resilience and land cover classifications. Their 'Picture Pile' project originally developed to assess deforestation has gone on to be developed into a range of other uses such as the Crowd4Sat initiative, which assesses high-resolution satellite imagery to support post-disaster damage assessment. In examples such as these, the citizen scientist can contribute directly to relief efforts (*e.g.*, post Hurricane Matthew, Haiti, Sept 2016). The project aims to facilitate rapid damage mapping using crowd-sourced data and satellite imagery to support humanitarian relief efforts and post-disaster

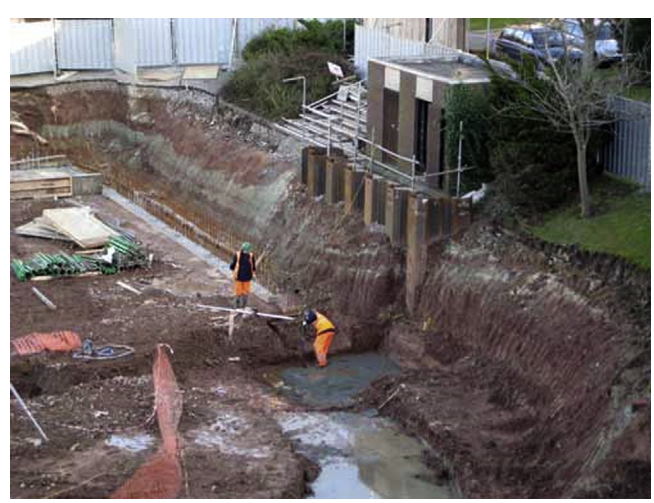

Fig. 1. A record for the BGS crowdsourcing app GeoExposures. May 2008 exposure in the foundations for the new William Smith Building.

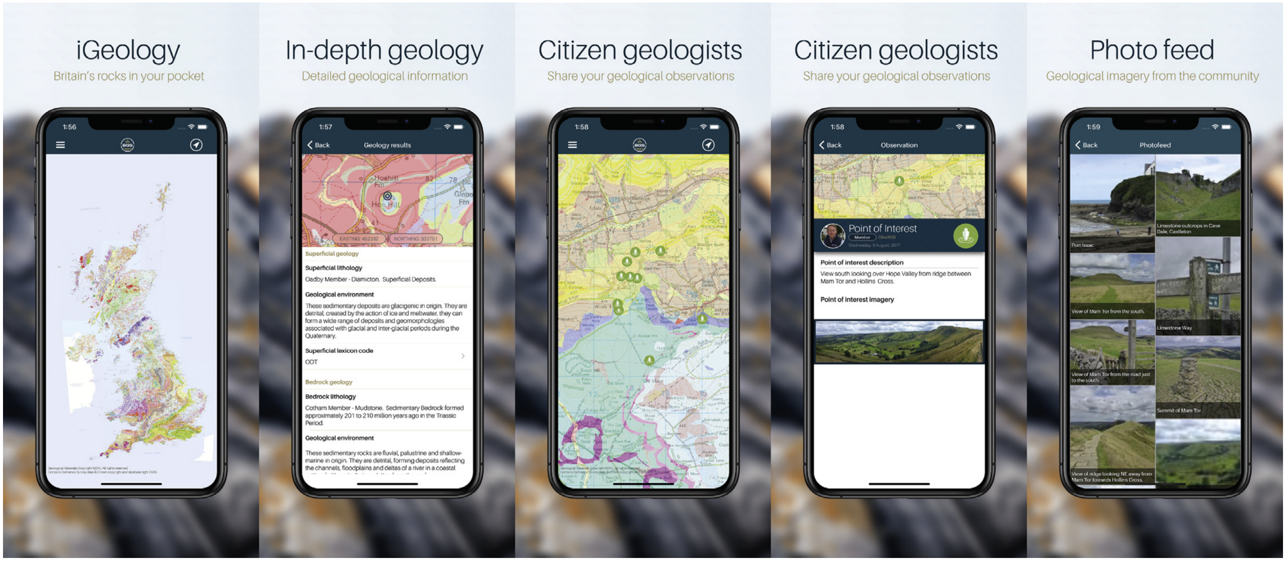

Fig. 2. BGS's iGeology App has a crowdsourcing element that was launched in 2019.

recovery. It is also pitched as a game, which can be played on a mobile device.

BGS, like many other national geological survey organisations, manages a number of national repositories composed of data provided from professional crowdsourcing activities, either voluntary donations or donations under statute. An example is the National Geotechnical Database, which is a composite database of donations from geotechnical companies including site investigation reports, boreholes, geotechnical tests, cross sections and maps. There are a number of ongoing activities and projects with the aim of increasing the amount of data provided such as the 'Dig to Share' project. It is estimated that *c.* 50% of construction project delays are reported to be caused by unforeseen ground conditions. A large proportion of the data generated by the UK Ground Engineering industry is 'single use', *i.e.*, used only in relation to the project that the investigation was commissioned for, and not shared with any adjacent or subsequent projects, as a result, some 80% of ground investigation records are 'missing' from the National Geotechnical Database. For example, basement extensions in several London boroughs require a hydrogeological study, however, this data is currently not collected. Dig to Share is aiming to improve the situation by developing a fully digital workflow, which is accessible to the whole industry, to upload and access such site investigation data. The BGS materials collection is as another example of a crowdsourced (Expert crowd) dataset. This data has been traditionally 'donated' to BGS over many decades however, in a modern context, could also be considered as 'expert crowdsourced'.

3.4. Education and Outreach

Citizen Science is not a one-way flow of information gathering from the citizen to the science project, there is also an important educational role that can be utilised, benefiting and empowering the citizen. Educating and engaging citizens about the topic, enables increased understanding and awareness and potentially a well-prepared and informed citizen who can act sustainably and considerately, contribute effectively to research, and help to tackle many of the issues affecting the quality of life and the environment.

One example of educational citizen science is the field course developed at James Madison University in Ireland, which specifically utilised a crowd with specific geological expertise to study the selection and recording of structural field observations at outcrop (Whitmeyer, 2014). There is an educational component to this that benefits the students taking part whilst continuing to build a detailed database of field recordings over multiple years. Whitmeyer (2014) provides an example of where university students effectively crowdsource geological mapping data via fieldwork, collate multiple users (students) and multiple years of field measurements and records. Over 2,000 students attend the field-training course each year and focus on a different unmapped area. The output is a 'consensus' geological map of good detail and accuracy in areas previously unmapped by professional geologists.

A younger audience is involved in citizen science through the UK Schools Seismology Project (Denton, 2008). In operation for a number of years, it deploys seismometers in schools to detect large earthquakes (UK and globally), which gather information to aid research as well as providing an educational role.

In 2015, the Quaternary Research Association (QRA) successfully utilised crowdsourcing to identify the Top 50 Quaternary sites in the UK (Fig. 3). The scheme was introduced during the 50th anniversary of the QRA to 'crowdsource' an inventory of the 50 most significant Quaternary sites in the UK. Over 80 sites were nominated and compiled within a Google Maps viewer, along with an accompanying digital publication (Silva and Phillips, 2015). A similar scheme was used in 2014 by the Geological Society as part

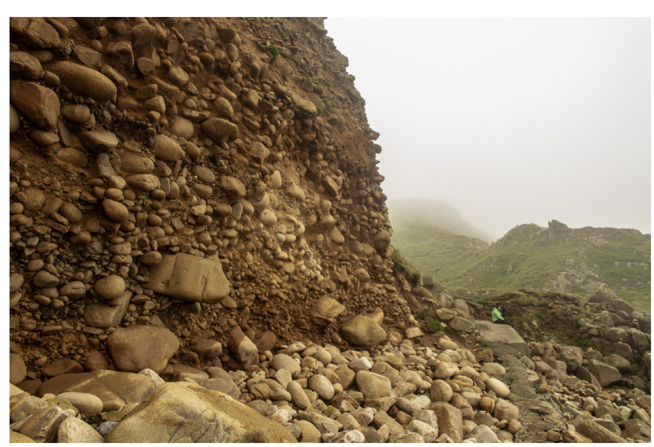

Fig. 3. Porth Nanven raised beach, west Cornwall. One of the Quaternary Research Association (QRA) Top 50 Quaternary sites in the UK as selected by Citizen Science (Photo: J. Lee).

of Earth Science week with '100 Great Geosites in the UK and Ireland'. These schemes helped to raise the profile of both societies, but also increased awareness of our landscape heritage and geoconservation potentially benefitting tourism. Whether these crowdsourcing activities can be truly classified as 'Citizen Science' is unclear. This is because whilst site nominations and explanatory text are clearly sourced to individuals or organisations, the level of 'citizen scientist' participation in both projects is not outlined.

4. Future Opportunities and Focusses

4.1. Future evolution of Citizen Science

Over the last decade the essential building blocks for utilising Citizen Science have been laid, trialled and tested in many forms. Many projects have provided 'lessons learned' and whilst some have dwindled, others have been hugely successful. In parallel to this, technology has, and continues to, develop and there are still many opportunities for researchers to benefit from this in a number of ways.

As knowledge of techniques and an understanding of how to create successful citizen science projects grows, there are increasing ***collaborative*** opportunities for projects to expand from single-use to more cross-organisation working in order to benefit research and to engage with citizen scientists. There is a danger however, that citizen scientists will become overwhelmed by the volume of different projects all vying for their attention. By broadening scope and developing multi-organisational collaborations, these issues can be reduced.

There is a growing opportunity to improve ***awareness*** of Citizen Science projects not just to connect people to science and its relevance, but at a project-specific level to aid communication of the project outcomes. Some projects do the latter well (e.g. the USGS's 'Did you feel it?') but the visibility of other citizen science activities is limited which ultimately undermines their sustainability. Future developments need to build on current platforms to provide discovery outputs with more information about the level of citizen science involvement, what it has contributed and how to access the data. The USGS have a particularly effective communication strategy in actively connecting people to science. They state (source: USGS news) the following five key benefits of using Citizen Science, which are also applicable to other scientific organisations around the world: (1) advancing and accelerating scientific research through group discovery and co-creation of knowledge (for example, engaging the public in specialized data collection can provide information at resolutions that would be difficult for an agency to obtain due to time, geographic, or resource constraints); (2) improving the quality and relevance of observations due to the unique perspectives and local knowledge citizen scientists bring to projects; (3) encouraging and increasing science literacy and providing students with skills needed to excel in science, technology, engineering, and maths (STEM); (4) improving delivery of government services with significantly lower resource investments; and (5) connecting citizens to the missions of federal/government agencies by promoting a spirit of open government and volunteerism for the common good.

Making data ***accessible*** and sharing crowdsourced data should be a key focus for future work. Enabling access to information and a wider audience is improving but is not necessarily well publicised, and organisations and groups need to improve the promotion of both projects and their results. One solution might be to enable easier access using cross-discipline platforms such as Zooniverse. There is currently a strong focus on engaging the citizen scientist and crowd at the initial start-up of a citizen science project, however in general much greater visibility is required on follow-up engagements and communication of the outputs and results.

An emerging need is to use, and better develop, the ***data standards*** around crowdsourced data to ensure findability, accessibility and interoperability. Large amounts of data could provide significant input to research projects but cannot be included if they are not easily accessible or shared. There is also a need to standardise outputs and publicise their ***accuracy*** and/or ***confidence*** in the data. For example, crowdsourced data via the BGS i-geology app is validated prior to publishing content, and although this process incurs an additional time and cost element, it does increase confidence in the data and safeguards data for future use. A review article by Zheng et al. (2018) considers the use of crowdsourcing within their seven selected domains of science (weather, precipitation, air pollution, geography, ecology, surface water and natural hazard management). They discuss the challenges of availability and uncertainty of geophysical data, which could equally be applied in other subjects – spatial and temporal resolution (e.g. rainfall during storm events), cost (*e.g.*, monitoring stations), and accessibility (*e.g.*, the physical terrain, power supply), availability (real-time data), uncertainty (quality of the data), and dimensionality (social interaction). The key challenges highlighted are those of processing the potentially large amounts of submitted data and the ability to differentiate the variability (*e.g.*, correction for bias, temporal variation, etc.). A further challenge are the issues of data privacy, particularly where non-volunteered, harvested data is gathered and it is suggested that in this area, there is still much to be researched and best practices shared.

It is often important to provide some form of benefit, ***reward*** or feedback in any Citizen Science project otherwise, there will be no impetus for the citizen scientists to spend their time and effort providing data and input. There is a recognised challenge in keeping citizen scientists engaged throughout the course of a project, especially if it is long-term (months - years) rather than short-term (days – weeks) in duration. It has been widely observed that citizen science activity usually peaks with some form of promotional event or campaign but these need to be complemented by other benefits. There are several methods in use, for example, the USGS has developed a successful scheme to reward contributions. Citizen scientists earn virtual badges for participating and are recognised for their contributions (with permission) via the USGS and National Map social media channels. The USGS regularly publish updates so citizen scientists can see progress and importantly see how the data is being used, which in-turn encourages participation. Additionally, in some cases, they seek citizen input, incorporating an element of co-design, where their suggestions can influence the next round of community projects. As mentioned previously, financial reward should be used cautiously, if at all, as it can undermine the sustainability of a project and promote unrealistic expectations.

4.2. Citizen science opportunities in Earth Science

Key future opportunities for citizen science in Earth Science occur within the fields of geoconservation and geohazards. Both of these areas have already made foundations in using citizen science techniques however, more opportunities could be exploited.

Geoconservation is a key area of interest, having developed and grown relatively rapidly, especially since the 1990's (Burek and Prosser, 2008; Whitely and Browne, 2013), attracting input from both professionals and volunteers alike. Looking to the future, there needs to be wider political and public support for geoconservation. However, this is unlikely until its reach is broadened and 'relevance' can be more effectively demonstrated (Prosser, 2013). Ongoing active participation is needed in order for geoconservation to evolve and one method to achieve this could be through the use of citizen science. Citizen science projects have the potential to broaden public engagement and interest in geoscience in the UK. An example of the use for crowdsourced data could be to help monitor, or assess, the 'condition status' of formally ('Site of Special Scientific Interest', SSSIs) and informally ('Local Geological Sites', LGS) (also known as Regionally Important Geological Sites (RIGS)) designated geological sites. This may help regulatory organisations (*e.g.*, Natural England, Scottish Natural Heritage/Nature.Scot, and Natural Resources Wales) and local societies prioritise resources more effectively. This could be especially relevant for Quaternary sites, which, due to their unconsolidated nature makes them vulnerable to ongoing degradation (*e.g.*, Bridgland, 2013). Capturing ephemeral condition data on these sites by crowdsourcing could enhance their management and ultimately their preservation.

There are increasing opportunities for Earth Science related topics to 'piggy-back' on other apps and citizen science programmes, including identifying opportunities that may not be obvious at first glance. For example, in the case of monitoring designated geoscience sites such as SSSI's, there is potential cross-over into apps such as 'Dumb Dumpers', where users can readily report fly tipping, using a simple app. Fly tipping can be a common problem at some designated sites impacting accessibility and safety. Such government sponsored tools can often also double-up as foci for other longer-term crowd sourcing initiatives such as the twitter based '@UKSoilErosion' where rural walkers monitor soil erosion by rivers. There is also a crossover into other formal schemes for crowdsourcing environmental damage, such as the tools provided by 'Scotland's environment web', managed by the Scottish Environment Protection Agency (SEPA), which is delivering a shared hub for crowdsourced environmental information and data. Here, engaged citizens can discover projects/campaigns requiring crowdsourced input and links to supportive tools and resources. There is also cross-over and opportunity for curating museum collections, building evidence and data. For example, a recent initiative run by the Natural History Museum recorded fossil species on part of the Jurassic Coast (Larwood, 2019). Such projects could be taken further and collaborations increased, benefiting museum collections as well as geoscience education.

In terms of opportunities in the geohazards sphere, much of the work has previously focussed on the high-impact global hazards (earthquakes and volcanology) however, lessons can be learnt and techniques can be re-assigned. For example, within the UK there is need for a more joined up approach to coastal management and data provision such as identifying and collecting data on the state of coastal defences. Diversification of opportunities is also important. For example, sensor data such as water levels or rainfall measurements are widely used and API's (application program interfaces) make the data openly available. However, lesser-known technologies such as soil moisture sensors (now commonly available as add-ons to home weather stations) are growing in sophistication. By thinking laterally and building on these, more options could become possible (*e.g.*, aid research into subsidence, shrink-swell and ground instability hazards). The use of air photo interpretation or satellite imagery (especially semi-automated) to 'map' changes in river courses could help to model and forecast flood and river scour threats, identifying coastal change pre- and post- storm events, and much more.

It is also worth considering the range of citizen scientists that participate in geology-focussed projects. Many citizen science projects target specific citizen groups such as local amateur groups, schools, professional engineers, etc. However, there are others (*e.g.*, on the Zooniverse platform, or the USGS) that have primarily aimed for mass-numbers rather than expertise and these rely upon the maintained motivation of the participants to be sustainable. These different citizen science activities require quite different approaches. The former group will potentially provide more informed, detailed data and give a higher degree of confidence. By contrast the latter will potentially provide a broader range of data (spatially) and much higher quantity. Whichever approach is selected will depend on the project requirements and objectives. The current small, more focussed studies have an opportunity to expand and develop into much larger programmes. For instance, there is significant potential for multi-disciplinary projects (e.g. geohazards such as flooding or coastal resilience), bringing together multiple groups and organisations, to achieve greater impact, message and results.

Crowdsourcing for the scientific study of the environment or society has so far, largely been driven by research investment but a more commercial aspect is also beginning to emerge. There have been some very clear success stories of research-driven citizen science such as the iRecord family of crowdsourcing projects. iRecord is a common platform developed by the Centre for Ecology and Hydrogeology (CEH) that enables seemingly distinct projects to use the same resources. Partner bodies can use this platform to quickly build campaigns for specific studies (*e.g.*, iRecord dragonflies, iRecord soil).

There is now significant private sector investment in building common-interface crowdsourcing platforms. These crowdsourcing-tool providers are responding to the private enterprise use of crowdsourcing in a more commercial way, *e.g.*, where businesses are 'buying into' a dedicated interface that uses a common backend of data (*i.e.*, behind the scenes technology such as databases, scripts). These crowdsourcing apps are commonly based around harvesting ideas and skills from participants and a contribution earns an agreed fee – this business model is more akin to traditional 'agency hire' piecework, etc. This provides firm evidence that industry has recognised the value of crowdsourced data. Apps are also being offered to enable a crowd with specific skills to be targeted and 'nudged' to take part (*e.g.*, Crowdicity, Topcoder). Crowdsourcing software coders and software developers also compete in crowdsourced software design challenges. Prizes can be considerable and provide a lucrative side-line for developers with league tables often used to monitor progress. This method uses a balance between harnessing time/effort skill from an expert and enough reward for the 'volunteer' that suits their lifestyle/interests.

Another consideration and an area for multiple opportunity and impact is in lower income countries. As mentioned previously, there are barriers to overcome, *e.g.*, organisational capacity, awareness, perceived value of data, and crucially, access to, and skills in, appropriate technology. However, some projects are starting to develop these opportunities. One example is the Philippines Groundwater Outlook (PhiGO) project, which is focussing on groundwater management under changing climate conditions, particularly in urban areas. Furthermore, the MyVolcano app has been piloted in the Caribbean including a trial for multihazard scenarios. Engaging with schools, governments and communities has aided research into improvements that could facilitate real-time decision-making (Duncan et al., 2017). However, examples from lower-income countries are still underrepresented in the citizen science literature and there remains multiple opportunities to utilise citizen science and work towards the UN's sustainable development goals.

5. Conclusions

The purpose of this paper has been to provide a review of citizen science within the earth sciences and reflect on future directions within the field. Citizen science activities have developed rapidly over the last decade typically reflecting an 'enabling' of both technology and volunteer citizen scientists who are engaging in ever-more sophisticated ways with professional scientists. Several key case study examples have been investigated to review the benefits and obstacles of these methods and how they are currently being employed within the earth sciences. This review has highlighted some emerging areas of continuing development, as well as potential new opportunities. The earth science research agendas, both in the UK and globally, could benefit from volunteered input, accelerating science research, and improving engagement with citizens, which can in-turn, encourage learning and improve understanding especially in areas such as disaster management. This review has also highlighted, as in the area of environmental science and conservation, that citizen science activities have a much greater visibility in western developed countries than in lower-income countries with social and structural barriers in the latter restricting more widespread usage.

In the field of earth science, crowdsourcing and citizen science projects that relate to the major global geohazards (*e.g.*, volcanoes, earthquakes) have provided proven case studies of success, benefitting both the broader science research community but have also supported local communities in terms of geohazard monitoring and disaster resilience. Ultimately, the impact of citizen science is measured by how the acquired knowledge is used to advance scientific understanding and / or integrated into policy, planning and decision making. In this respect, the impact of citizen science to-date has been mixed and whilst it has global potential, its potential has not yet been fully realised.

Successful citizen science projects require a clear vision and strategy for achieving these end goals to overcome inevitable strategic and operational challenges. Successful projects also require good planning, strategic milestones, and strong engagement with communities to recruit and retain volunteers as well as ensure effective dissemination of the science. Building and maintaining an effective citizen science project should at least consider several key factors: (1) a clear vision of what the project is trying to achieve and the anticipated outcomes; (2) a clear understanding of the motivation for volunteers and their social and cultural context; (3) effective communication between professional and citizen scientists throughout the project and clear strategy for dissemination information during and after the project; (4) identification of the type of data that can realistically be gathered by the volunteers and protocols for data collection, submission and QA.

Planned correctly, earth science research has the potential to benefit from these citizen science techniques, providing access to large amounts of new data, both spatially and temporally, that would otherwise not be possible to achieve by single projects or organisations alone. There are abundant challenges but also many opportunities to accelerate research, particularly the potential to boost the pace of data acquisition, and to improve engagement in lower-income countries, which are too great to disregard. Citizen scientists are increasingly aware of the earth, its processes and its influences on everyday life. Many want to engage, to protect the environment, access resources and contribute to scientific research that ultimately helps to fuel the economy, and citizen science has a growing role to play in this process.

Citizen Science at the British Geological Survey: https://www.bgs.ac.uk/citizenScience/home.html

Citizen OBservatory Web project COBWEB: https://cobwebproject.eu/

CITIZAN project: https://www.citizan.org.uk/

Crowd4Sat Initiative: http://www.crowd4sat.org/

Crowdicity: https://crowdicity.com/product#grow=EAIaIQobChMI2vK7npOp5wIVyLTtCh25pga8EAAYAiAAEgICcvD_BwE

CrowdHydrology: http://www.crowdhydrology.com/

Crowdwater: https://crowdwater.ch/en/welcome-to-crowdwater/

Did you see it? (USGS): https://www.citizenscience.gov/catalog/124/#

Dig to Share: https://www.i3p.org.uk/projects/digtoshare/

Dumb dumpers: https://www.zerowastescotland.org.uk/DumbDumpers

Exposures (BGS): https://www.bgs.ac.uk/citizenScience/EXposures.html

FINTAN: Ordnance Survey (OS) crowdsourced gazetteer of 'local' names and places. https://www.ordnancesurvey.co.uk/business-and-government/case-studies/maritime-coastguard-agency-deploys-vernacular-geography.html

M.A. Finkelstien. Intrinsic vs. extrinsic motivational orientations and the volunteer process Personality and Individual Differences 2009; 46: 653-658.

GeoExposures (BGS): https://www.bgs.ac.uk/citizenScience/geoexposures.html

Geological Society 100 Great Geosites: https://www.geolsoc.org.uk/100geosites

GeoSocial (British Geological Survey): https://www.bgs.ac.uk/citizenScience/geosocial/home.html

i-Mars project: http://www.i-mars.eu/index.php, web GIS: http://www.i-mars.eu/

iRecord: https://www.ceh.ac.uk/news-and-media/news/new-app-record-full-range-uk-wildlife

*my*Soil app (BGS): https://www.bgs.ac.uk/mysoil/

*my*Volcano app (BGS): https://www.bgs.ac.uk/myVolcano/

Philippines Groundwater Outlook (PhiGO) project: https://gtr.ukri.org/projects?ref=NE%2FS003118%2F1#/tabOverview

Quaternary Research Association (QRA) Top 50 Quaternary sites in the UK: https://www.qra.org.uk/top-50-quaternary-websites/

Report a landslide (BGS): https://www.bgs.ac.uk/landslides/reportForm.html

Scotland's environment web: https://www.environment.gov.scot/get-involved/

Topcoder: https://www.topcoder.com/

UK Soil Erosion Twitter: @UKSoilErosion https://twitter.com/uksoilerosion?lang = en-gb

United Nationals Sustainable Development Goals: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

United States Geological Survey National Map Corps (TNMCorps): https://www.usgs.gov/core-science-systems/ngp/tnm-corps

United States Geological Survey iCoast: https://coastal.er.usgs.gov/icoast/

United States Geological Survey Volunteer Recognition: https://navigator.er.usgs.gov/help/vgistructures_rewards.html

USGS citizen science key benefits news article: https://www.usgs.gov/news/citizen-science-citizens-science-and-planet

Waze navigation app: https://www.waze.com/en-GB/

Zooniverse: https://www.zooniverse.org/

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References

Alabri, A., Hunter, J., 2010. Enhancing the quality and trust of Citizen Science data. 2010 IEEE Sixth International Conference on e-Science, IEEE, pp. 81–88.

Atkinson, G.M., Wald, D.J., 2007. Did You Feel It?" intensity data: A surprisingly good measure of earthquake ground motion. Seismological Research Letters 78, 362–368.
Boatwright, J., Phillips, E., 2012. Exploiting the demographics of "Did You Feel It?" responses to estimate the felt area of moderate earthquakes. 84th Annual Meeting of the Eastern Section of the Seismological Society of America. Virginia Polytechnic Institute and State University, Blacksburg, Virginia 28–30 October 2012.
Bee, E., Coulon, P., Robbins, J., Tomlinson, J., 2012. Hazard Map – Real time hazard mapping using social media. Association for Geographic Information, Geocommunity 2012 conference paper.
Bol'shakov, V.A., Kapitsa, A.P., Rees, W.G., 2012. James Croll: a scientist ahead of his time. Polar Record 48, 201–205.
Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K.V., Shirk, J., 2009. Citizen Science: a developing tool for expanding science knowledge and scientific literacy. BioScience 59, 977–984.
Bonney, R., Shirk, J.L., Phillips, T.B., Wiggins, A., Ballard, H.L., Miller-Rushing, A.J., Parrish, J.K., 2014. Citizen science. Next steps of citizen science. Science 343, 1436–1437.
Bonney, R., Phillips, T.B., Ballard, H.L., Enck, J.W., 2016. Can Citizen Science enhance public understanding of science? Public Understanding of Science 25, 2–16.
Bossu, R., Landès, M., Roussel, F., Steed, R., Mazet-Roux, G., Martin, S.S., Hough, S., 2017. Thumbnail-Based Questionnaires for the Rapid and Efficient Collection of Macroseismic Data from Global Earthquakes. Seismological Research Letters 88, 72–81.
Bridgland, D.R., 2013. Geoconservation of Quaternary sites and interests. Proceedings of the Geologists' Association 124, 612–624.
Burek, C.V., Prosser, C.D. (Eds.), 2008. The History of Geoconservation. 300. The Geological Society of London, Special Publications, pp. 312pp.
Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., De Biévre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D.H., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., Tilahun, S., Van Hecken, G., Zhumanova, M., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. Frontiers in Earth Science 2, 26.
Cambridge Online Dictionary, 2019. https://dictionary.cambridge.org/dictionary/english/crowdsourcing.
Cieslik, K., Shakya, P., Uprety, M., Dewulf, A., Russell, C., Clark, J., Dhital, M.R., Dhakal, A., 2019. Building Resilience to Chronic Landslide Hazard Through Citizen Science. Frontiers in Earth Science 7, 278.
Chandler, M., See, L., Copas, K., Bonde, A.M.Z., López, B.C., Danielsen, F., Legind, J.K., Masinde, S., Miller-Rushing, A.J., Newman, G., Rosemartin, A., Turak, E., 2017. Contribution of citizen science towards international biodiversity monitoring. Biological Conservation 213B, 280–294.
Cohn, J.P., 2008. Citizen Science: Can volunteers do real research? BioScience 58, 192–197.
Cooper, C.B., Shirk, J., Zuckerberg, B., 2014. The Invisible Prevalence of Citizen Science in Global Research: Migratory Birds and Climate Change. PLoS ONE 9 (9), e106508. doi:http://dx.doi.org/10.1371/journal.pone.0106508.
Cope, J.C.W., 2016. Jurassic Ammonites and stratigraphy: papers celebrating the life of John Hannes Callomon 7 April 1928-1 April 2010. Proceedings of the Geologists' Association 127, 127–131.
Conrad, C.C., Hilchey, K.G., 2011. A review of Citizen Science and community-based environmental monitoring: issues and opportunities. Environmental Monitoring Assessment 176, 273–291.
Crall, A.W., Newman, G.J., Stohlgren, T.J., Holfelder, K.A., Graham, J., Waller, D.M., 2011. Assessing Citizen Science data quality: an invasive species case study. Conservation Letters 4, 433–442.
Danielsen, F., Burgess, N.D., Balmford, A., 2005. Monitoring Matters: Examining the Potential of Locally-based Approaches. Biodiversity & Conservation 14, 2507–2542.
Denton, P., 2008. Seismology in schools: 10 years on. Astronomy & Geophysics 49 (6), 13–14.
Dickinson, J.L., Zuckerberg, B., Bonter, D.N., 2010. Citizen Science as an ecological research tool: challenges and benefits. Annual Review of Ecology, Evolution, and Systematics 41, 149–172.
Doyle, C., David, R., Li, Y., Luczak-Roesch, M., Anderson, D., Pierson, C.M., 2019. Using the Web for Science in the Classroom: Online Citizen Science Participation in Teaching and Learning. Proceedings of the 10th ACM Conference on Web Science, ACM, Boston, Massachusetts, USA, pp. 71–80.
Duncan, M., Mee, K., Hicks, A., Engwell, S., Robertson, R., Forbes, M., Ferdinand, I., Jordan, C., Loughlin, S., 2017. Using the' myVolcano' mobile phone app for citizen science in St. Vincent and the Grenadines: a pilot study. British Geological Survey. Open Report 43pp OR/17/045.
Gardiner, M.M., Allee, L.L., Brown, P.M., Losey, J.E., Roy, H.E., Smyth, R.R., 2012. Lessons from lady beetles: accuracy of monitoring data from US and UK citizen-science programs. Frontiers in Ecology and the Environment 10, 471–476.
Geoghegan, H., Dyke, A., Pateman, R., West, S., Everett, G., 2016. Understanding motivations for science. Final report on behalf of UKEOF. Univeristy of Reading, Stockholm Environment Institute (University of York) and University of the West of England, pp. 120pp.
Guerrini, C.J., Majumder, M.A., Lewellyn, M.J., McGuire, A.L., 2018. Citizen science, public policy. Science 361, 134–136.
Gura, T., 2013. Citizen Science: Amateur experts. Nature 496, 259–261.
Haywood, B.K., 2014. A "Sense of Place" in Public Participation in Scientific Research. Science Education 98, 64–83.
Haklay, M., 2013. Citizen Science and Volunteered Geographic Information – overview and typology of participation. In: Sui, D.Z., Elwood, S., Goodchild, M.F. (Eds.), Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice. Springer, Berlin, pp. 105–122.
Higgins, C.I., Williams, J., Leibovici, D.G., Simonis, I., Davis, M.J., Muldoon, C., van Genuchten, P., O'Hare, G., Wiemann, S., 2016. Citizen OBservatory WEB (COBWEB): A Generic Infrastructure Platformto Facilitate the Collection of Citizen Science data for Environmental Monitoring. International Journal of Spatial Data Infrastructures Research 2016 (11), 20–48.
Huddart, J.E.A., Thompson, M.S.A., Woodward, G., Brooks, S.J., 2016. Citizen science: from detecting pollution to evaluating ecological restoration. WIREs Water 2016 (3), 287–300.
Irwin, A., 2018. No PhDs needed: how citizen science is transforming research. Nature 562, 480–482.
Kong, Q., Allen, R.M., Schreier, L., Kwon, Y.-W., 2016. MyShake: A smartphone seismic network for earthquake early warning and beyond. Science Advances 2.2 doi:http://dx.doi.org/10.1126/sciadv.1501055.
Kosmala, M., Wiggins, A., Swanson, A., Simmons, B., 2016. Assessing data quality in Citizen Science. Frontiers in Ecology and the Environment 14, 551–560.
Kullenberg, C., Kasperowski, D., 2016. What Is Citizen Science? – A Scientometric Meta-Analysis. PLOS ONE 11, e0147152.
Liang, W.-T., Lee, J.-C., Hsiao, N.-C., 2019. Crowdsourcing Platform Toward Seismic Disaster Reduction: The Taiwan Scientific Earthquake Reporting (TSER) System. Frontiers in Earth Science 7, 79.
Larwood, J., 2019. The Jurassic Coast: Geoscience and education – An overview. Proceedings of the Geologists' Association 130, 265–273.
Leigh Star, S., Griesemer, J.R., 1989. Institutional ecology, 'translations' and boundary objects: amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social Studies of Science 19, 387–420.
Loos, J., Horcea-Milcu, A.I., Kirkland, P., Hartel, T., Osváth-Ferencz, M., Fischer, J., 2015. Challenges for biodiversity monitoring using citizen science in transitioning social-ecological systems. Journal for Nature Conservation 26, 45–48.
Marsnik, S.J., Lorentz, R.M., 2015. Who owns employee works? Pitfalls in a globally distributed work environment. Chapter 8. In: Oswald, L.J., Pagnattaro, M.A. (Eds.), Managing the Legal Nexus Between Intellectual Property and Employees.. Edward Elgar Publishing, Cheltenham, pp. 226–255.
McKinley, D.C., Miller-Rushing, A.J., Ballard, H., Bonney, R., Brown, H., Evans, D.M., French, R.A., Parrish, J.K., Phillips, T.B., Ryan, S.F., 2015. Investing in Citizen Science can improve natural resource management and environmental protection. Issues in Ecology 2015, 1–27.
Navakanesh, B., Shah, A.A., Prasanna, M.V., 2019. Earthquake Education Through The Use of Documentary Movies. Frontiers in Earth Science 7, 42.
Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of Citizen Science: emerging technologies and shifting paradigms. Frontiers in Ecology and the Environment 10, 298–304.
Noè, L.F., Gómez-Pérez, M., Nicholls, R., 2019. Mary Anning, Alfred Nicholson Leeds and Steve Etches. Comparing the three most important UK 'amateur' fossil collectors and their collections. Proceedings of the Geologists' Association 130, 366–389.
Oberle, K.M., Page, S.A., Stanley, F.K.T., Goodarzi, A.A., 2019. A reflection on research ethics and citizen science. Research Ethics 15, 1–10.
Paul, J.D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J.A., Bhusal, J., Cieslki, K., Clark, J., Dugar, S., Hannah, D.M., Stoffel, M., Dewulf, A., Dhital, M.R., Liu, W., Nayaval, J. L., Neupane, B., Schiller, A., Smith, P.J., Supper, R., 2018. Citizen science for hydrological risk reduction and resilience building. Wiley Interdisciplinary Reviews: Water 5, e1262.
Pearce, F., 2018. How a janitor wowed Darwin by solving the ice age mystery. New Scientist 22 (08), 2019.
Pocock, M.J.O., Tweddle, J.C., Savage, J., Robinson, L.D., Roy, H.E., 2017. The diversity and evolution of ecological and environmental citizen science. PLoS ONE 12, e0172579.
Pocock, M.J., Roy, H.E., August, T., Kuria, A., Barasa, F., Bett, J., Githiru, M., Kairo, J., Kimani, J., Kinuthia, W., Kissui, B., Madindou, I., Mbogo, K., Mirembe, J., Mugo, P., Muniale, F.M., Njoroge, P., Nijuguna, E.G., Olendo, M.I., Opige, M., Otieno, T.O., Ng'weno, C.C., Pallangyo, E., Thenya, T., Wanjiru, A., Trevelyan, R., 2019. Developing the global potential of citizen science: Assessing opportunities that benefit people, society and the environment in East Africa. Journal of Applied Ecology 56, 274–281.
Powell, J., Nash, G., Bell, P., 2013. GeoExposures: documenting temporary geological exposures in Great Britain through a citizen-science website. Proceedings of the Geologists' Association 124, 638–647.
Prosser, C.D., 2013. Our rich and varied geoconservation portfolio: the foundation for the future. Proceedings of the Geologists' Association 124, 568–580.
Raddick, M.J., Bracey, G., Carney, K., Gyuk, G., Borne, K., Wallin, J., Jacoby, S., Planetarium, A., 2009. Citizen Science: status and research directions for the coming decade. AGB Stars and Related Phenomenastro 2010: The Astronomy and Astrophysics Decadal Survey, 2010. , pp. 46pp.
Rasmussen, L.M., Cooper, C., 2019. Citizen Science Ethics. Citizen Science Theory and Practice 4, 1–3.
Resnik, D.B., 2007. The price of truth: How money affects the norms of science. Oxford University Press.
Resnik, D.B., 2011. Scientific Research and the Public Trust. Science and Engineering Ethics 17, 399–409.

Resnik, D.B., Elliott, K.C., Miller, A.K., 2015. A framework for addressing ethical issues in Citizen Science. Environmental Science and Policy 54, 475–481.
Riesch, H., Potter, C., 2014. Citizen Science as seen by scientists: Methodological, epistemological and ethical dimensions. Public Understanding of Science 23, 107–120.
Rochford, K., Strauss, J.A., Kong, Q., Allen, R.M., 2018. MyShake: Using Human-Centred Design Methods to Promote Engagement in a Smartphone-Based Global Seismic Network. Frontiers in Earth Science 6, 237.
Rosen, J., 2013. Citizen Scientists help the Shale Network address fracking concerns. Vision Learning Available at:. . https://www.visionlearning.com/blog/2013/01/10/citizen-scientists-shale-network-address-fracking-concerns/.
Rossiter, D.G., Liu, J., Carlisle, S., Zhu, A.X., 2015. Can Citizen Science assist digital soil mapping? Geoderma 259-260, 71–80.
Roy, H.E., Pockock, M.J., Preston, C.D., Roy, D.B., Savage, J., Tweddle, J.C., Robinson, L. D., 2012. Understanding Citizen Science and environmental monitoring. Final Report on behalf of UK Environmental Observation Framework. NERC Centre for Ecology and Hydrology (CEH) and Natural History Museum (NHM), Wallingford, Oxfordshire.
Sauermann, H., Franzoni, C., 2015. Crowd science user contribution patterns and their implications. Proceedings of the National Academy of Sciences 112, 679–684.
See, L., 2019. A Review of Citizen Science and Crowdsourcing in Applications of Pluvial Flooding. Front. Earth Sci. 7, 44. doi:http://dx.doi.org/10.3389/feart.2019.00044.
Seibert, J., Strobl, B., Etter, S., Hummer, P., van Meerveld, H.J., 2019. Virtual Staff Gauges for Crowd-Based Stream Level Observations. Frontiers in Earth Science 7, 70.
Shah, A.A., Khawaja, S., Shah, B.A., Reduan, Q., Jawi, Z., 2018. Living With Earthquake and Flood Hazards in Jammu and Kashmir, NW Himalaya. Frontiers in Earth Science 6, 179.
Sherman, A., 2015. CITiZAN: Community Archaeology Around the English Coastline. The Journal of Council for British Archaeology Yorkshire. 4, 25–28.
Show, H., 2015. Rise of the citizen scientist. Nature 524, 265.
Shamoo, A.E., Resnik, D.B., 2009. Responsible conduct of research. Oxford University Press.
Shamoo, A.E., Resnik, D.B., 2015. Chapter 11 - The Protection of Human Subjects in Research. In: Shamoo, A.E., Resnik, D.B. (Eds.), Responsible Conduct of Research. Oxford University Press, Oxford, pp. 236–282.
Silva, B., Phillips, E., 2015. UK top Quaternary sites: compilation to celebrate the QRA's semi-centennial year. Quaternary Research Association, London, pp. 111.
Silvertown, J., 2009. A new dawn for Citizen Science. Trends in ecology & evolution 24, 467–471.
Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M.A., Parrish, J.K., 2015. Global change and local solutions: Tapping the unrealized potential of Citizen Science for biodiversity research. Biological Conservation 181, 236–244.
Torrens, H.S., 2006. Notes on 'The Amateur' in the development of British geology. Proceedings of the Geologists' Association 117, 1–8.
West, S., Pateman, R., 2016. Recruiting and Retaining Particpants in Citizen Science: What Can Be Learned from the Volunteering Literature? Citizen Science: Theory and Practice 1 (15), 1–10.
Whitely, M.J., Browne, M.A.E., 2013. Local geoconservation groups - past achievements and future challenges. Proceedings of the geologists' Association 124, 674–680.
Whitmeyer, S.J., 2014. EOS, Transactions, 95. American Geophysical Union, pp. 397–408 44.
Wiggins, A., Crowston, K., 2015. Surveying the Citizen Science landscape. First Monday 2015, 20.
Wilde, A., Kreuzer, O., 2016. The role of crowdsourcing in gold exploration. Australian Institute of Geoscientists Newsletter 124, 38–43.
Zheng, F., Tao, R., Maier, H.R., See, L., Savic, D., Zhang, T., Chen, Q., Assumpcao, T.H., Yang, P., Heidari, B., Rieckermann, J., Minkser, B., Bi, W., Cai, X., Soltomatine, D., Popescu, I., 2018. Crowdsourcing methods for data collection in geophysics: state of the art, issues, and future directions. Rev. Geophys. 56, 698–740. doi: http://dx.doi.org/10.1029/2018RG000616.