Extreme Citizen Science Contributions to the Sustainable Development Goals: Challenges and Opportunities for a Human-Centred Design Approach

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Abstract. Citizen science has been recognized for its potential to contribute to the UN Sustainable Development Goals in multiple ways (e.g., for defining and monitoring indicators, data production, etc). In this paper, we focus on Extreme Citizen Science, which includes a set of situated, bottom-up practices, used for environmental monitoring purposes and for recording local indigenous knowledge, mainly in the Global South. Here we present and discuss the human-centered approach that the implementation of extreme citizen science requires, and we identify and discuss the challenges that we face as well as the opportunities that extreme citizen science initiatives can create for contributing to the Sustainable Development Goals.

Keywords: Extreme Citizen Science, Sustainable Development Goals, Human-Centered Design

1 Introduction

Citizen science is defined as the 'scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions' [1]. Citizen science projects have recently gained increased momentum, mainly as a result of technological developments including the availability and increasing use of mobile devices. There is a plethora of citizen science activities that cover a wide range of topics from pollution monitoring to bird watching and other ecological monitoring activities to astronomy [2]. Apart from contributing to scientific discovery, citizen science activities are also used for advocacy purposes and volunteer-initiated participatory action to address issues of local concern [3].

Since 2017, the contributions of citizen science to the Sustainable Development Goals (SDGs) at the goal and/or target level have been the subject of several workshops. Moreover, it has been recognised that citizen science has the potential to contribute to the SDGs by: explicitly contributing to the indicators and transforming the SDGs so that their measurement is better aligned to people's experiences; acting as a spatial proxy for monitoring indicators with specified methodologies and engaging citizens in data production; and implementing the interventions and actions based on evidence as well as providing mechanisms to accelerate the achievement of the targets [4,5].

This paper discusses the role of a particular form of public participation in research, called extreme citizen science [22], where participants have more control over the design and implementation process than in citizen science projects more generally. To date, these initiatives have focused on environmental monitoring and capturing traditional ecological knowledge, mainly in the Global South. Due to the contextual conditions and the characteristics of the communities that are engaged in extreme citizen science, a human-centred design approach is required for the application of the methods. It is also required for the development of the technological infrastructure, which is used to assist local communities in data collection and analysis so that they can identify locally appropriate solutions to tackle local issues. Here we emphasise the challenges that we face in applying extreme citizen science and the opportunities that this brings in achieving the Sustainable Development Goals (SDGs).

2 Citizen Science and its Role in Sustainable Development

2.1 The Sustainable Development Goals (SDGs)

The United Nations Sustainable Development Goals (SDGs) consist of a set of goals that aim to tackle a range of social, environmental and economic issues, as well as a set of metrics that are used to track their progress in order to achieve a sustainable world by 2030. Tracking SDG progress in a timely, accurate and efficient way is essential for ensuring their successful delivery. Conventional data, which are commonly used to monitor SDG progress such as household surveys, are important for providing reliable and useful insights, but they are expensive, resource-intensive, and inadequate for tracking all 231 unique indicators in the SDG framework [6,7,8]. Citizen science - defined as public participation in scientific research and knowledge production - can support the monitoring of SDGs as a new data source to provide timely, relevant and reliable information with a higher temporal and spatial resolution, which can either be used on their own or for complementing more conventional data sources [6,7,9].

The potential offered by citizen science for SDG monitoring and their implementation has been widely discussed in the more recent academic literature [6,7,10,11,12,13]. In fact, evidence - from a comprehensive review of SDG indicators and citizen science initiatives at the local, regional and global levels - suggests that citizen science data are already contributing or have the potential to contribute to the monitoring of 33% of the SDG indicators [6]. The authors also demonstrated that the SDGs that could benefit most from citizen science data include: SDG 15 Life on Land; SDG 11 on Sustainable

Cities and Communities; SDG 3 on Good Health and Wellbeing and SDG 6 on Clean Water and Sanitation [6]. The greatest contributions of citizen science to SDG monitoring are, therefore, to the environmental SDG indicators. It is also important to highlight that 58% of the 92 environmental SDG indicators lack data, and thus the role of citizen science data in monitoring the SDGs becomes even more crucial. For example, at the indicator level, the contributions from citizen science to SDG monitoring may cover areas such as marine litter (indicator 14.1.1b), rural access (9.1.1), threatened species (15.5.1), post disaster damage (1.5.2), air quality (3.9.1), water quality (6.3.2), land use and land cover (15.1.1, 15.2.1) and sexual violence (16.1.3), among others.

There have been ongoing efforts at the UN level to include citizen science in the methodologies for SDG monitoring. For example, the global methodology for SDG indicator 14.1.1b on plastic debris density explicitly mentions the use of citizen science approaches, particularly for the monitoring of beach litter [15,16]. UNEP has also been providing financial and operational support to citizen science initiatives, with the aim to improve their methodologies and match them to the monitoring requirements of SDG indicator 14.1.1b [14].

It has been already mentioned that citizen science can complement SDG monitoring efforts at a national, regional, and global level. Citizen science can achieve this through the participation of volunteers and communities in data collection activities that focus on the local level. Capturing this local knowledge and local wisdom from volunteers and local communities provides an irreplaceable source of information that is essential for bridging community level initiatives with global monitoring efforts. Additionally, although not always possible as we discuss later, local citizen science initiatives may leverage the SDG framework to support their data collection activities and therefore, ensure that the data collected feeds directly into the official monitoring schemes.

Although citizen science in the context of sustainability and the SDGs has started to gain increasing recognition by the wider academic community more recently, it should be noted that the majority of citizen science efforts mainly concentrate on the advanced economies of the Global North, enabled by social trends such as access to education, exposure to science and the wide use of digital technologies. There is a more recent realization that citizen science can demonstrate significant local and global impacts and that it has the potential to contribute to the global sustainability agenda based on evidence from successful citizen science initiatives, which can also address issues in the Global South. For example, [17] discuss citizen science as an innovation mechanism and highlight that in opening up participation in science, “it is equally important to include indigenous and local knowledge as an added benefit to science, for example, in framing questions, designing projects, analysing results and understanding their possible impacts upon decision-making processes”. Moreover, [18] demonstrate that “both ILK [indigenous local knowledge] and institutionally derived scientific understanding can be valuable in conservation planning activities. This knowledge inclusivity can bring specific expertise to citizen science projects and embed the results in the community affected” [18;468].

We make the argument, and further discuss in this paper, that in line with the “leaving no one behind” principle of the 2030 Agenda for Sustainable Development, it is extreme citizen science activities that can operate in local indigenous environments in remote locations, provide insights into how people interact with their local environment, generate environmental data for areas where data gaps exist, and subsequently make the monitoring of SDGs more inclusive and impactful.

2.2 Citizen Science and Extreme Citizen Science

Several definitions and terms have been used to describe citizen science, capturing the disciplinary perspective or the unique cultural, geographical and scientific characteristics of the discipline and context in which citizen science is being implemented. Despite this potpourri of definitions, there is consensus that citizen science can be broadly described as the involvement of non-professional scientists in scientific research and knowledge production. Some scholars from the field of citizen science have provided in-depth theoretical and practical perspectives on how citizen science is currently being utilised through the lens of different hierarchies or taxonomies, for example, Shirk's five models of participation in scientific research [19]; Haklay's 4-level hierarchy [20]; and Cooper's 5Cs model of participation [21]. In Fig. 1, we present Haklay's [22] hierarchy.

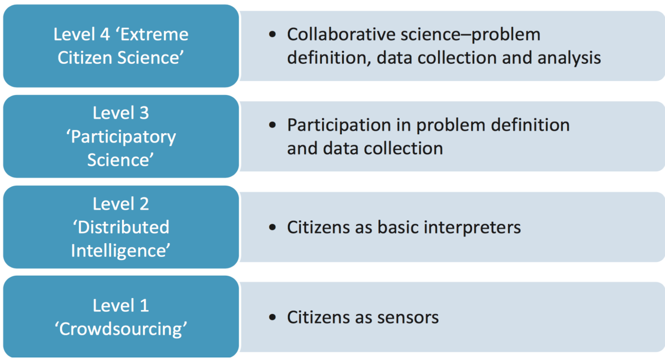

Fig. 1. Levels of engagement in citizen science [22].

Haklay's hierarchy (Fig.1.) includes four levels: level 1 'crowdsourcing', where participation happens at much larger scales, with activities that mainly focus on sharing resources (e.g., computer power) rather than requiring any significant cognitive effort; level 2 'distributed intelligence', where participants contribute to data collection or interpretation tasks and which, therefore, involve some cognitive effort; level 3 'participatory science', where participants contribute not only to data collection and interpretation but also in forming the research questions and problem definition; and level 4 'extreme citizen science', where participants can be involved at all stages of the scientific process. In other words, extreme citizen science gives any community the support they need to conduct collaborative science - including problem definition, data collection and analysis - for issues that matter to them and which they decide they want to tackle.

In UCL's Extreme Citizen Science (ExCiteS) group, they define extreme citizen science as a philosophy of situated, bottom-up practices that take local needs, practices and cultures into account and that work with broad networks of people in order to design and build new devices as well as knowledge creation processes that can make positive transformations in the world. In the next section, we present a set of extreme citizen science initiatives and their methods and tools in order to build a better understanding of how our work in extreme citizen science has the potential to promote sustainable development.

3 Extreme Citizen Science: Methods and Tools

Extreme citizen science initiatives use a set of methods and technologies that have been developed to support individuals and communities in the collection of traditional ecological knowledge, environmental data for monitoring and other data to address issues that communities want to tackle. Subsequently, communities or individuals engage in data collection processes that allow them to collect the evidence required to prove the existence of these specific local problems - for example, to local governmental authorities - and eventually to take the necessary steps to resolve them.
Below we list a few examples of extreme citizen science initiatives that mainly concentrate on the Global South:

Tackling Illegal Wildlife Crime and Animal Monitoring with the Baka Communities in Cameroon. Dja Biosphere Reserve, home to Baka hunter-gatherers and Mbulu farmers of Cameroon, has traditionally been used to provide its local populations with a large variety of plants and animals to support their livelihoods. However, it is currently being depleted by the illegal wildlife trade and extractive industries, while existing conservation legislation excludes indigenous communities and their knowledge and turns them into conservation refugees. Local communities, with the support of local NGOs, use extreme citizen science to collect data about illegal wildlife crime and animal monitoring, with the aim to collect evidence that will eventually be used to inform effective forest management legislation [23].

Collecting Data for Indigenous Plants with Maasai warriors in Kenya. One of the greatest threats that Maasai communities in Narok county, Kenya, face is the loss of traditional ecological knowledge and the increased deforestation in the Maasai Mara National Reserve. Therefore, local communities rely on extreme citizen science tools to collect indigenous plant data, with the aim to pass this knowledge onto future generations and preserve it. Since 2019, they have collected thousands of observations of the medicinal and other properties of local indigenous flora.

Managing Natural Resources for New Conservation Legislation with Indigenous Communities in the Pantanal Wetlands, Brazil. The Pantanal is the largest wetland in the world, with local fishers being totally dependent on it for their daily livelihoods. Legislation for resource management and consumption in the area does not consider people's traditional practices, and this has resulted in their physical and economic displacement. Local communities have used extreme citizen science since 2014 to collect data on their fishing practices, which provide evidence to demonstrate that indigenous practices are indeed sustainable; as a result, the local people have been officially recognised as a "traditional community". This has legally given them the right to protect their livelihoods and continue using their traditional natural resource management practices [24].

Managing Natural Resources and Fighting Illegal Cattle Invasions with the Ju/'hoansi in Namibia. The Nyae Nyae Conservancy in Namibia, officially registered in 1998, has come under threat since the local communities have come into contact with agricultural economies and due to the extensive cattle farming in traditional hunting and gathering grounds. As the primary custodians of the conservancy, the Ju/'hoansi use extreme citizen science methods and tools to collect data that can help them tackle the issues of illegal cattle invasions in their territory, and more recently, they also collect data that will eventually help them to manage their local community forest resources [25].

It has been already mentioned that in extreme citizen science, and the examples mentioned above, that each community identifies the problem(s) they want to tackle, and hence, the purpose and the cultural, contextual and environmental characteristics vary. Moreover, the majority of the extreme citizen science initiatives, including the ones described above, include communities with varying levels of literacy, with no access to technological infrastructure (e.g., electricity, Internet access, etc.) and without previous exposure to digital technology (e.g., smartphones, data collection apps, online maps, etc.). These are just a few of the challenges that we face in the majority of extreme citizen science projects. Therefore, despite the differences in contextual characteristics, all extreme citizen science initiatives follow a very similar methodological framework and utilise the same set of technologies (modified to fit each context), which are designed to support these communities, and which are constantly being improved to deal with additional challenges. Before we describe the opportunities and challenges in more detail, we introduce the extreme citizen science methodology and tools in the Sections 3.1 and 3.2.

3.1 Engagement in Extreme Citizen Science

All extreme citizen science initiatives rely heavily on a participatory design approach methodology, informed by anthropological and Human-Computer Interaction methods. The same methodological steps are followed during the development and iterative design of extreme citizen science practices, and the development and adaptation of our tools to fit the context of each initiative.

As communities identify the problems to address, engagement is mostly initiated by the communities themselves (or local organisations that support these communities). A set of preliminary meetings with local communities, their trusted gatekeepers and local intermediaries then take place to identify or further discuss their local issues and to develop a mutual understanding of how extreme citizen science can be best utilised to support them. Once this is established, an engagement process is then applied as described below.

Free, Prior and Informed Consent Process (FPIC). The FPIC process aims to inform "the affected persons about planned activities and their impacts" and verify "that the information provided has been understood, before explicit consent can be negotiated" [26]. The consent is free and informed, highlighting the ability of communities to refuse an intervention, and it takes place prior to them being affected by any external actions [26]. While the FPIC process is a prerequisite for many studies that include human participants, here the process relies heavily on taking local cultural frameworks into account (e.g., local protocols, hierarchies, etc.) and communicating what constitutes consent. This process, which is explained in detail in [27] further sets the foundations for local capacity building [26; 28].

Establishment of a Community Protocol. Community protocols are used to establish the expectations of communities in the conduct of the initiative and formalise the terms collectively agreed. They are also crucial in sustaining each initiative over its lifetime. The community protocol documents a detailed plan capturing issues such as: who will be collecting the data, when will data collection take place, how will the data be stored, how will equipment be managed, issues of data security, access and sovereignty, support provision (e.g., technical, methodological, logistical) and others. Potential risks and other implications are explored collaboratively in community protocol designated meetings, which take place throughout the duration of the initiative, as terms need to be redefined when new concerns or issues arise or the situation changes (e.g., new actors are involved), and solutions are co-designed. In this process, as [27] explain, communities are encouraged to lead discussions, and particular care is taken to ensure that everyone feels encouraged to express their views without any criticism or judgment.

Participatory Design for the development and evaluation of locally appropriate and relevant technologies. Extreme citizen science initiatives target communities where education and literacy, access to technological infrastructure and familiarity with technology and local environmental conditions present various obstacles to their successful adoption and utilization, as we discuss in more detail in Section 4.1. Most of the communities we work with are either technically and/or textually illiterate or have low levels of literacy, and hence, research in the development and design of our tools and methods draws upon the fields of Human-Computer Interaction for Development (HCI4D), mainly with respect to the use of iconic interfaces, menu structures and information organisation (for further information see [28]).

Our main data collection tool, Sapelli Collector, which is discussed in more detail in the next section, uses a pictorial interface and a hierarchical decision tree to represent an ontology of data items for which information is collected. The pictorial icons (Fig. 2) used by Sapelli Collector are co-designed with the communities involved to ensure that local meanings and cultural conventions are taken into account and so that the icons are well understood. This is an iterative process; for example, if decision trees are shown to be too complex, we co-design alternative solutions, either by simplifying the project (e.g., see [30]), or even introduce alternative technologies such as Tap&Map [31].

Fig. 2. Community workshop for designing Tap&Map pictorial icons for data collection [31].

Ethnographic observation is used to understand how technologies are used locally, paying particular attention to challenges and how use is shaped by contextual and environmental conditions, and social organisational structures. Human-computer interaction methods (usually modified to be locally appropriate) are also used to explore and improve interaction with extreme citizen science tools. In our participatory design process, emphasis is placed on reciprocity and giving back to the community (e.g., helping with daily activities; spending significant time to learn the local culture, language and participate in social activities; building friendships; and learning from each other and passing on new skills etc.). Our vision, similar to [32], is to "promote empowerment, through technology, enabling people to become better equipped so that they can innovate for themselves" [32;243], rather than focusing solely on innovation in the first place.

3.2 Extreme Citizen Science Tools

In the following, we provide a brief overview of the main technological tools used in extreme citizen science initiatives, which are mainly used for data collection for environmental monitoring purposes as well as for capturing local indigenous knowledge.

Sapelli Collector. Sapelli is an Android-based, open source mobile data-collection and -sharing application, designed with a particular focus on users with low or no literacy and little or no prior ICT experience. The application executes surveys, which take the form of pictorial decision trees (Fig. 3.) based on hierarchical ontological structures that describe the data items being collected. The leaves represent specific answers or classifications, while in-between nodes represent categories of similar items. Users navigate the decision tree by repeatedly 'tapping' images to select child nodes until they reach a leaf node, which represents the data item being collected (i.e., audio, photos, geospatial coordinates, etc.).

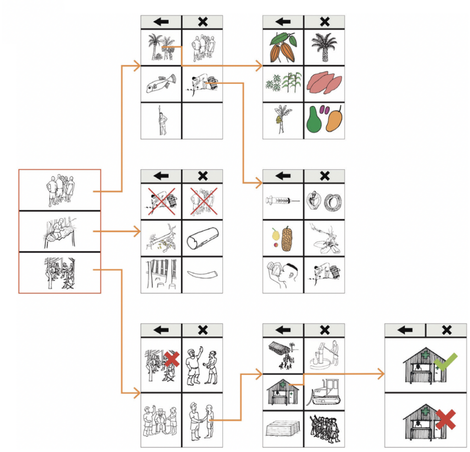

Fig. 3. Sapelli Collector interface design and decision tree [31].

Tap&Map. Preliminary testing of Sapelli Collector in Congo has shown that local participants had difficulty navigating its hierarchical structure - a finding consistent with the wider HCI4D literature in terms of how people with low levels of literacy navigate hierarchical data structures [34;35] – as well as other issues (e.g., fear of using technology, difficulties with the touchscreen, etc.) [31]. A more accessible user interface, Tap&Map, was developed to tackle these challenges. It consists of a series of physical cards, each with a pictogram representing the data item being collected and an Android application. Using cards with near field communication (NFC) tags, the user must identify the card for which information is being collected, and then they touch it on the phone while standing as close as possible to the actual location of the physical object so that the application registers the correct coordinates. Tap&Map then reads the user's location from the device's Global Positioning System (GPS) sensor and stores it, along with other necessary metadata recorded by the user (e.g., photos, audio).

Sapelli Viewer. A common expectation across communities involved in extreme citizen science initiatives is the need to view data instantly, or soon after the data are recorded. To support this need, we are currently developing Sapelli Viewer, which is a data visualisation application for Android devices (i.e., smartphones and tablets) that also includes basic (e.g., select and view all crop type 'A') and advanced data filtering options (e.g., view changes of crop 'A' in different time periods), enhancing the application's analytic capabilities, the types of spatial thinking that it will support and how this could potentially be used to develop and apply more effective local environmental management strategies.

4 Extreme Citizen Science for Environmental Monitoring in the Global South: Opportunities and Challenges

Citizen science attracts people of all ages, backgrounds and interests. Although this has its own massive design challenges, citizen science has generally focused on a limited demographic profile of Western, educated, people from industrialized, rich and democratic nations [36], where the educational skills and basic access to, and familiarization with, digital technologies are usually taken for granted. Extreme citizen science initiatives include communities in remote areas, where technological infrastructure and familiarity with technology, education and literacy, as well as environmental conditions, present various obstacles to their successful adoption and utilization. At the same time, local cultural contexts and knowledge structures create new opportunities to further our understanding with respect to environmental management and sustainability. It is for these reasons that a human-centred design approach is absolutely essential.

In the next two sections, we discuss the challenges that we face in extreme citizen science, which require the adoption of a human-centred design approach (4.1). Secondly, we discuss the opportunities that citizen science and extreme citizen science can bring to the monitoring of the SDGs (4.2) and to the global sustainability agenda, especially if they are to be implemented effectively and efficiently in a way that further empowers and protects local actors and their voices.

4.1 Challenges

The challenges posed by extreme citizen science depend on several contextual factors. If we take a step back, remove the unique contextual characteristics and the challenges that these create, and then look at the broader context of extreme citizen science, we can identify two major sets of challenges that are common and exist in the majority (if not all) of our initiatives. First, we have challenges that refer to data-related issues (e.g., data ownership, security, accuracy, etc). Secondly, we face challenges that emerge mainly due to specific technological and educational barriers and that influence how extreme citizen science is being implemented and practiced in areas where these barriers exist. We discuss these challenges in more detail in the paragraphs that follow.

There is an ongoing debate in the broader academic literature of citizen science around data quality issues. For example, top-down citizen science projects, led by professional scientists, rely heavily on large numbers of volunteers collecting data at large scales, which then allows research questions to be explored using a spatial coverage that would otherwise be impossible and that improves the scientific understanding of the topic for which data are being collected (e.g., ecology and biodiversity citizen science projects such as the Christmas Bird Count). In this context, common data quality concerns may refer to the reliability and quality of the data collected, or they may be due to volunteer training and the skill of the "non-expert" as opposed to that of a professional scientist, as well as variations in the sampling efforts and the coverage, which may introduce further bias, among other issues.

With extreme citizen science initiatives, which have a much smaller geographic focus, the data collection is only possible by working directly with local communities in a bottom-up way. This allows for investigation into what these communities need and how professional scientists can support them through the provision of the appropriate local capacity building mechanisms and tools. In this way, communities can invest their time and effort in the activities appropriately that serve their specific aims. Although western beliefs about techno-scientific innovation and top-down approaches have long been proven to be problematic, and exclude local communities from the global environmental sustainability agenda, it is still 'difficult for people from "advanced" cultures to accept the idea that people from "primitive" cultures might know something scientifically significant' [37;14]. Subsequently, they may not challenge the data quality of these approaches on this basis. Considering the fact that these communities are integral to how their local environments are shaped, and they possess a wealth of local knowledge that is completely neglected by conventional scientists (e.g., not only in terms of the data that they collect, the cultural norms and meanings behind it, but also the way monitoring and data collection actually occurs), we need to rethink arguments about the scientific validity of these data and their assessment via conventional scientific standards of quality. This is particularly important not only when extreme citizen science data become the only available data source for remote geographic regions, but also that it is being used to complement other scientific data sources in terms of promoting equality, inclusiveness and ensuring that 'no one is left behind'. By bringing local knowledge and traditional expertise together, emerging collaborations can promote conservation and sustainable development.

Other data related challenges within the context of extreme citizen science that may further influence how efficiently this data source may be used in the context of sustainable development goals are data ownership and security issues. Communities in extreme citizen science, through the FPIC process (Section 3.1), take complete ownership of the project and the data being collected. However, there are cases in which communities may decide that they do not want to share their data because of data sensitivity and a lack of trust (e.g., unrecorded traditional ecological knowledge that indigenous communities do not wish to share with outsiders) or that extra measures for protection and security need to be taken into account due to adverse local conditions and local political power dynamics [38,39].

Data-related challenges are not the only ones we face in extreme citizen science. The majority of these initiatives rely on an entire technological ecosystem, yet the presence of such an ecosystem cannot be taken for granted, especially if it is used to engage with communities in remote, rural areas. Lack of electricity and wireless coverage create various obstacles in engaging with extreme citizen science, which necessitates identifying creative solutions (e.g., for charging the devices that are used to support data collection or visualisation tasks, updating the software to continue with the current tasks over long periods of time, etc.). Moreover, lack of access and familiarity with the technological infrastructure means that communities usually face difficulties managing the equipment that is used (e.g., phones, tablets, cables, chargers, converters, etc.) and for which training and support are required over long periods of time.

Interaction with smartphones and tablet devices relies heavily on on-screen gestures (e.g., swipe, long tap, short tap, pinch) and knowledge of interface design metaphors, which cannot be assumed. For example, some communities may have never used such devices before, or they may be illiterate or have low levels of literacy. Considering that most western interface design creations assume a certain level of textual literacy, this means extensive training needs to be provided in the use of technological equipment as well as research and ongoing testing to understand how to design user-friendly interfaces that can be utilised successfully by the intended audience. Within that context, the above-mentioned technological tools cannot rely on ontological structures that are derived from western knowledge systems, as evidence shows that when systems "are organised according to an externally imposed exogenous structure, [they] will become graveyards of objects no longer accessible to the practices of indigenous knowledge traditions and that knowledge captured in such a way is more in danger of being lost or misunderstood" [33; 240]; therefore ongoing research - which is highly context specific - is further required to develop tools that are culturally appropriate and ideally match, from an ontological point of view, the local knowledge systems. Considering these complexities, these initiatives usually require additional funding to support local capacity building, technical training, regular environmental data monitoring, equipment maintenance, etc.

Having mentioned that context specific research is needed to develop culturally appropriate and user-friendly extreme citizen science tools to support data collection for environmental monitoring and local indigenous knowledge, it should be further noted that anthropological and HCI methods, which are traditionally used for this purpose, require adaptation. First, with respect to HCI methods, we have previously discussed how conventional HCI methods are not culturally universal, they rely on assumptions, and therefore, we need to identify and design experiments that are locally appropriate (e.g., group usability testing for egalitarian communities, proxy user testing, etc.) [28,29]. Secondly, with respect to participatory methods, as [33] explain, these "must be considerably devised to ensure successful community engagement" (245). The authors propose that the implementation of culturally appropriate methods of engagement should answer questions such as "what will happen to the resulting knowledge, who really stands to benefit from the research, and how will the community benefit from the engagement" (243). They also suggest that instead of focusing on solutions "to overcome or compensate for something lacking", the emphasis should be on a "rhetoric of engagement, that promotes empowerment through technology" (243). Our methodological framework (i.e., with the FPIC, community protocol, etc.) aspires to the same vision and attempts to overcome these challenges; by placing reciprocity at the centre of our engagement approach, we attempt to establish familiarity, build mutual respect and establish trust with the communities with whom we work (e.g., see [39]). This is perhaps one of the greatest obstacles to be overcome, as past or even current projects that have engaged with the same communities have left a set of unfulfilled promises, resulting in a legacy of distrust [39].

Last but not least, the sustainability of extreme citizen science initiatives relies heavily on sustaining participant motivation and eventually 'closing the loop' by supporting communities to innovate themselves, or in other cases, expose the issues that they face (through the data collected and the analysis) and create some positive impact, as identified by the community itself. With respect to motivation, the majority of the initiatives are conceived by communities, and they are shaped around local issues; therefore, there is a high level of intrinsic motivation. Various challenges remain, and these concern, amongst others, the mobilisation of relevant stakeholders (when and if the community protocol supports it) whose involvement might be necessary for achieving change, the continuation of funding to support local communities, as well as questions about how to best take this body of local knowledge into account to more effectively address the environmental challenges we face.

4.2 Opportunities

The opportunities that extreme citizen science initiatives are offering in the context of SDG implementation and monitoring are many, and by using the examples described above, we can identify some of the ones that are potentially relevant within the 2030 agenda.

First, they offer a significant way to achieve the principle of "no one left behind". In a world in which literacy is very common, there is marginalisation and exclusion for people with little or no literacy. As a result, their knowledge and views about their environment are frequently excluded from statistical efforts including the SDG indicators. The education-related targets of SDG 4 aim to provide quality education and lifelong learning for all, especially for those who lack the skills to read or write. To achieve these targets, the UNESCO Institute for Statistics, in collaboration with the Global Education Monitoring (GEM) Report, have presented new data and policymaking tools to Member States that will help to produce and use indicators for monitoring and achieving SDG 4 at the national level. Yet within the national and local levels, we still need to identify culturally acceptable ways for all potential local communities to be part of the data collection and sharing efforts, so that they can gain representation and a voice within these larger scale processes, which are also linked to the access and distribution of resources.

Secondly, and which is now becoming widely recognised within UN reports such as the Global Environmental Outlook 6 or those produced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), traditional ecological knowledge is now accepted as a valuable source of environmental knowledge. The approaches that we describe here open up the possibilities for setting up mechanisms to collect and share such knowledge in a way that will ensure control over the data by the community and which also benefits the people who collect it. With the support of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), the establishment of digital data infrastructure is encouraged to enable the integration, coordination, connectivity and expansion of local multi-source datasets. Such infrastructures for measuring, comparing and monitoring the inclusive progress of the SDGs can facilitate the registration and sharing of new global indicators. For example, cloud services with big data and artificial intelligence can revolutionize environmental and resource monitoring to track the SDGs. Google, Amazon and Alibaba have their own cloud computing products, which could help to archive environmental data, e.g,, from gauging stations, Google Earth Engine (GEE), the Amazon Web Service (AWS) or the Alibaba Cloud. While this by itself will not solve the challenges of extractive and colonial science, it can create the conditions to address them.

Finally, the approach that we describe here can be extended with the use of sensors and other forms of data collection and sharing at the community level. Through cloud services, SDGs in any region of interest in the world can be monitored and tracked at any time and in any place. Appropriate sensors can be used to assess the quality of water resources, or record samples from the environment that can serve different SDG indicators. RiverWatcher is an example of such a model in China; since 2019, thousands of patrols from all over the country have provided regular monitoring along with rubbish clean ups through the Alipay mini program 'Xunhebao'. The fact that many of these communities live in a remote location opens up the possibility for improving the spatial and temporal coverage of different datasets. Here the FPIC and the community protocol can be used to ensure that equitable compensation is provided to those who collect the data, as well as improving their ability to find ways to utilize the information.

5 Conclusions

As noted previously, citizen science already contributes to the monitoring of 33% of the SDG indicators. Moreover, there are ongoing efforts at the UN level that are attempting to extend the utilisation of citizen science further in the context of SDG monitoring in order to improve the data coverage, especially for the 58% of the 92 environmental SDG indicators for which the data are not available. Citizen science has the potential to capture local knowledge and information that is often only available within local communities, and which provides an irreplaceable source of information essential for bridging community level initiatives with global monitoring efforts. Although the majority of current citizen science initiatives focus on the Global North, here we have discussed how extreme citizen science is currently being utilised in the Global South and that this work is important for several reasons. First, it brings us closer to realising the "leaving no one behind" vision of the 2030 Agenda for Sustainable Development. Secondly, an extreme citizen science approach is well suited to local indigenous environments in remote locations for which hardly any data exist, making, when possible, the monitoring of SDGs more inclusive and impactful. Thirdly, through extreme citizen science initiatives, we actually recognise the importance of traditional ecological knowledge that indigenous communities have relied on for millennia, and we make an effort to incorporate this knowledge into the global sustainability agenda.

Despite these potential benefits, the successful implementation of extreme citizen science initiatives to support environmental monitoring and the collection of local indigenous knowledge, in diverse cultural, environmental and infrastructural contexts, requires focusing attention on local specificities, and the careful consideration of how these specificities can inform the design of the tools and strategies for implementation. We found that anthropological and HCI methods are key in this process, as it is a participatory design process for the development and adaptation of extreme citizen science tools to a specific geographic and socio-cultural context. It is only through the human-centered design approach for implementing extreme citizen science initiatives that we can improve our ability to more effectively translate local knowledge into data sets that can be placed in dialogue with current scientific conservation and environmental management policy models and eventually contribute to the SDGs.

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