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Review

Smartphone technologies supporting community-based environmental monitoring and implementation: a systematic scoping review

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ABSTRACT

The prospect of leveraging new technologies for community-based environmental monitoring has captured the imagination of many scientists, policy makers, and conservation professionals. This systematic review examines the state of knowledge and trends in the peer-reviewed literature related to the use of smartphone technologies for community and citizen science environmental monitoring. We organize our findings in relation to data collection and data handling, the process of developing smartphone applications, and the ways that outcomes are reported. While the literature is nascent and technological advances are continually opening new opportunities, it is notable that there is limited scholarship that explicitly connects the monitoring function of smartphones to tangible conservation action (e.g., only 10 percent of the papers analysed data collected by smartphones, let alone making connections to required actions or policy). We discuss two central implications in terms of research-implementation spaces for environmental monitoring with smartphones: (1) what we identify as the cost paradox, the lack of recognition of actual costs of app development, monitoring, and implementation; and (2) the need to center the role of people and partnerships in order to ask more precise questions about outcomes for app users and conservation impacts from data collection. We conclude with a call for more research on costs and actual impacts, documentation of factors that lead to successes and failures, and how digital divides influence conservation outcomes. Our intent is not to call into question the potential impacts of smartphone technologies, but to encourage further understanding of how and when they can be most useful.

1. Introduction

Monitoring is a key activity to understand changing environmental conditions and inform conservation efforts. While such monitoring was conventionally the domain of trained professionals, the rise in availability and sophistication of smartphone technologies is having a direct influence on the ability of the public to collect and share environmental data (Teacher et al., 2013; Chapron, 2015). Data can be collected through integrated sensors on smartphones (e.g., built in camera, GPS, microphone), add on sensors (e.g., specialized tools attached via cable or Bluetooth), and complemented by the entry of personal observations with made-for-purpose applications. The benefits promoted with new technologies include more efficient, less expensive, and less intrusive tracking of environmental conditions (including animals and plants) (August et al., 2015; Pimm et al., 2015; Sullivan and Molles, 2016). Potential integration of social networking also means there are opportunities to engage non-professional scientists in environment and wildlife monitoring in ways that were not previously possible.

The natural resource management literature has long emphasized the need for timely and locally-relevant information about environmental conditions to support learning and decision-making (Holling and Meffe, 1996; Armitage et al., 2009). Similarly, the biological conservation literature has identified the need for evidence-informed decisions (Sutherland et al., 2004; Adams and Sandbrook, 2013). There has also been broad recognition of the value of involving local people in monitoring to integrate their interests, values, culture, and skills into programs to manage and conserve ecosystems (Stephanson and Mascia, 2014; Kohler and Brondizio, 2017). Greater involvement of individuals and communities is advocated as a means to incorporate local and indigenous knowledge systems (Berkes et al., 2007; Raymond et al., 2010), generate trust and credibility for monitoring projects (Kouril et al., 2016), build relationships between local people and authorities

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(Danielsen et al., 2009), and help subvert power imbalances that affect marginalized people (Kellert et al., 2000; Barbour and Schlesinger, 2012; Wilson et al., 2018).

Increasingly, smartphone technology is playing a role in catalyzing public and community involvement. A recurring message from researchers is the importance of matching appropriate technology for specific problems and specific participants (Connors et al., 2012; Newman et al., 2012; Teacher et al., 2013; McKinley et al., 2017). Best practices include consideration of appropriate technologies, who and how technologies will be developed, data collection protocols, data management and sharing options, recruiting and retaining participants, participant privacy, and sufficiency of time and resources (for further reading see Newman et al., 2012; Ferster and Coops, 2013; Teacher et al., 2013; Sturm et al., 2017; Luna et al., 2018).

However, there is not a full understanding of the conditions needed for smartphone technologies to facilitate the collection of useful data that can inform environmental conservation research, policy, and practice. To address this need we present a systematic scoping review of the peer reviewed literature examining what is known about how smartphone technologies have been leveraged to contribute to community level environmental monitoring. We frame our review around research-implementation spaces, seeking to identify specific areas where collaboration is needed around important topics (Toomey et al., 2017). Ultimately, we hope to promote a discussion about whether and how smartphone-based data collection is benefiting environmental monitoring at the community level, informing policy development or conservation initiatives.

We begin by contextualizing our review through the citizen science literature and focus on how mobile technologies are used for environmental monitoring. In the methods section we describe our approach to this systematic scoping review, including the steps we took for data collection, screening, and analysis. Our findings focus in on the ways that the peer review literature reports on data collection and handling, the process for software application development, and research outcomes, to bring attention to lessons that can be drawn from this qualitative literature analysis.

1.1. Community-based environmental monitoring and the emergence of mobile technologies

Citizen science refers to the participation of members of the public in any aspects of scientific research (Eitzel et al., 2017). We use this term because it is broadly familiar, recognizing that terms such as crowdsourcing, public participation in scientific research (PPSR), volunteered geographic information (VGI), and community-based research have also been used in comparable contexts (for commentary on the use and implications of these terms see Wiggins, 2012; Cooper and Lewenstein, 2016; Eitzel et al., 2017). Citizen science is multi-faceted and contributes to scientific knowledge, public education, and the empowerment of citizens. Our interest here is to overview how the literature on citizen science has treated the use of smartphone technologies for environmental monitoring.

Smartphone technologies are challenging the norms for how science is conducted and the role of public participation in research processes. The general public had been largely excluded from scientific processes (observations, measurements, interpretation) in recent decades and communication technologies provide new tools enabling ‘amateur’ scientists to participate in many aspects of science (Devisch and Veestraeten, 2013; Preece, 2016). The internet has increased the visibility and reach of citizen science projects (Bonney et al., 2014; Pocock et al., 2017). Newman et al. (2012) discussed how the use of new technologies shift processes for data collection, potentially improve data management and quality control, and enhance communication. Since much of the data collected tends to be ad hoc rather than systematic, questions have arisen about data quality and emphasis has been placed on devising new means of analysis and interpretation (Hochachka et al., 2012; Bonney et al., 2014; Preece, 2016).

There are many forms of participation and engagement in research projects (see Shirk et al., 2012; Haklay, 2013), which influence the potential role of smartphone technologies. These forms of participation and engagement include: (a) the public only as data collectors; (b) the public in helping refine problem definition and data collection design and maybe with analysis, and; (c) the public as co-creators who are involved with all aspects of project framing, data collection, interpretation, and knowledge sharing. Haklay (2013) asserted that there are merits to each type of engagement and that we should not place value on one type of participation as better than the others. When we consider smartphone technology use by the public, it is important to keep in mind that monitoring (data collection) is only one aspect of engagement. Smartphones have potential use for communication among participants, interpretation and analysis of data, and information or results sharing. Projects often also make use of websites so that participants can add data on either their computer or smartphone (Mazumdar et al., 2018). Websites can sometimes offer more functionality, whereas smartphone applications (hereafter “apps”; small software programs designed for specific uses on mobile devices, such as smartphones and tablets) offer transportability and the ability to enter data from anywhere that is geo-tagged and time-tagged.

Novelty can influence why researchers and project managers choose to adopt particular smartphone technologies for citizen science. There is an allure and excitement for the potential to be seen as cutting edge and innovative. Jepson and Ladle (2015, p.827) exhibited the optimism and enthusiasm often written about smartphones and apps: “They have the potential to transform how humans interact with nature, cause a step change in the quantity and resolution of biodiversity data, democratize access to environmental knowledge, and reinvigorate ways of enjoying nature.” Confidence can also be seen in Preece's (2016, p.585) call to “save all species” globally through citizen science and the use of mobile technologies to improve conservation and education. Verma et al. (2016) tempered this enthusiasm with an analysis of how the use of smartphone technology adds new expectations and pressures on research and conservation organizations and can (sometimes negatively) influence narratives around wildlife conservation and human-nature interactions. Silver and Hawkins (2017) also discussed how web-based technologies have the power to shape public discourse and influence the form and function of conservation agendas.

There is a sizeable literature that investigates motivations for participation in citizen science involving smartphone technologies. For example, volunteers are motivated to participate when they have a pre-existing interest or concern in the phenomena being monitored, have time and access to technology, and see real prospects to contribute to scientific research and society in general (Newman et al., 2012; Baruch et al., 2016; Brovelli et al., 2016; Wald et al., 2016; Leao and Izadpahani, 2016). Moreover, retention of volunteers is linked to a sense of belonging, with gamification (e.g., online competition or problem solving) being one effective strategy to keep people involved (Baruch et al., 2016; Newman et al., 2012).

Even so, mobile technologies do not always garner intended results. Challenges identified within the literature include: getting appropriate tools and information to the right people; the assembly and management of mass quantities of data; ensuring high quality data collection; and standardization of data formats for interoperability (August et al., 2015; Pimm et al., 2015). This reflects the importance of the human dimensions involved in data collection alongside technical issues that can arise. A study from Brammer et al. (2016) found that use of digital data entry was affected more by the design and implementation of overall projects than on the technologies themselves. In other words, clear planning for how to deal with data entry, analysis, and interpretation are key aspects to using mobile technologies effectively.

Table 1
Search string used in Scopus, Web of Science, ProQuest, and GeoBase. The operator ‘AND’ was used to combine the four sections.

Question components	Search terms
Activity	monitor* OR observ* OR surveillance OR record OR collect* OR inventory OR measurement OR identif* OR gather OR manage
Environmental context	environment* OR ecosystem* OR “natural resource*” OR conservation OR “resource management” OR species OR water OR wildlife OR ecolog* OR marine OR terrestrial OR biodiversity
Community context	“citizen science” OR community-based OR “community based” OR local-level OR “community science” OR “crowd science” OR “crowd-sourced science” OR “civic science” OR “volunteer monitoring” OR “networked science” OR participat* OR “local communit*” OR “community monitoring” OR “community groups” OR end-users OR landowners OR non-expert OR stakeholders
Smartphone technology	app OR apps OR smartphone OR “smart phone*” OR “mobile phone*” OR “mobile device*” OR “cell phone*” OR “cell phone technology” OR “cellular phone*” OR “mobile technolog*” OR iPhone OR iPod OR iPad OR Android

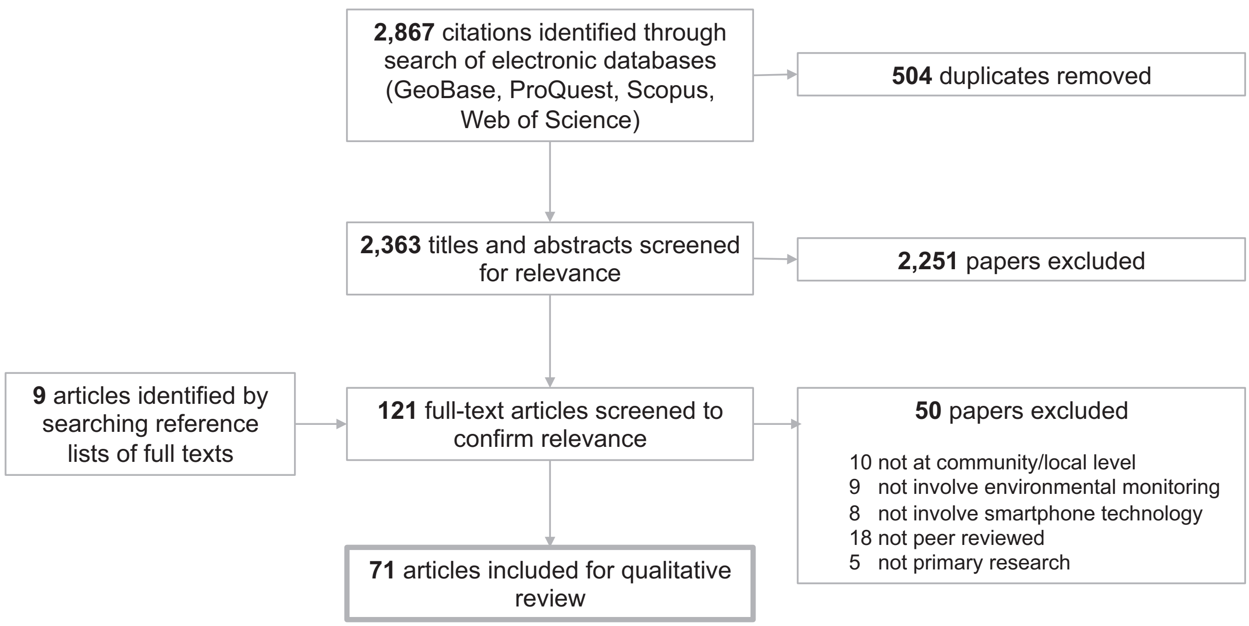

Fig. 1. Flow chart of the selection of studies.

2. Methods

We characterize our study as a systematic scoping review since we are focused on a critical appraisal of the state of knowledge regarding smartphone and community-based monitoring, and in identifying important spaces for improving research (Arksey and O'Malley, 2005; Berrang-Ford et al., 2015). We apply a rigorous, replicable search strategy that is the hallmark of systematic reviews, and a critical appraisal of the scope, strengths, and weaknesses of the literature (Levac et al., 2010). Our review consisted of five stages: (1) research question identification, (2) development of a search protocol, (3) literature search, (4) screening of collected literature, and (5) analyses.

Four databases were selected to comprehensively and extensively gather global literature – Scopus, Web of Science, ProQuest, and GeoBase – through consultation with a university librarian. This combination provided good coverage of the scholarly research across the natural and social sciences. A search query was developed and pilot tested across several databases to assess and improve the strength of the search. The final search string (Table 1) was applied consistently across all four databases. We limited the search to title-abstract-keyword since papers with a substantial focus on smartphones and environmental monitoring would include our search terms within these fields. No search restrictions were placed on geographic location or date of publication, except for the date restrictions built into the databases themselves. As smartphone technologies are relatively new, our assumption was that search terms would self-limit to recent years. A supplementary search included hand-searching citations in key publications and journals.

All results from the database searches were first uploaded to Mendeley software (Mendeley, 2018) to manage references and remove duplicates. Two levels of screening (title and abstract screening and then full text screening) were then conducted by two of the authors using Covidence online software (Covidence, 2018). Conflicts between reviewers were discussed in person until reviewers came to an agreement. We limited our inclusion criteria to only English publications due to practical considerations and language limitations of the research team (full inclusion and exclusion criteria are outlined in Appendix A). We decided to focus only on peer reviewed primary research publications to place an emphasis on empirical findings.

The first step in our analysis was to scope and characterize the literature. A questionnaire was used to gather basic information from all papers (Appendix B). The second activity involved thematic and open coding (categorization of text according to known and emergent themes) of the texts to identify relevant issues and linkages in the literature (Braun and Clarke, 2006). Coding was conducted using NVivo software (NVivo, 2018). Results are presented using a narrative approach – representation of findings that explores relationships within and between studies – to provide a synthesis of the relevant literature.

3. Results

Since this was an exploratory review the results are organized according to issues that emerged through our analysis. We begin with an overview of key characteristics of the studies we review and then discuss how the literature reports on data collection and handling, the app development process, and research outcomes.

Table 2
List of papers included in analysis and focal apps within each paper.

	Citation	Related apps
1	Adriaens, T., Sutton-Croft, M., Owen, K., Brosens, D., Van Valkenburg, J., Kilbey, D., Groom, Q., Ehmig, C., Thürkow, F., Van Hende, P., Schneider, K., 2015. Trying to engage the crowd in recording invasive alien species in Europe: Experiences from two smartphone applications in northwest Europe. Management of Biological Invasions 6, 215–225. https://doi.org/10.3391/mbi.2015.6.2.12	RINSE That's Invasive, KORINA
2	Aitkenhead, M., Donnelly, D., Coull, M., Hastings, E., 2014. Innovations in Environmental Monitoring Using Mobile Phone Technology – A Review. International Journal of Interactive Mobile Technologies (IJIM) 8, 42–50. https://doi.org/10.3991/ijim.v8i2.3645	[22 apps reviewed]
3	Bacco, M., Delmastro, F., Ferro, E., Gotta, A., 2017. Environmental Monitoring for Smart Cities. IEEE Sensors Journal 17, 7767–7774. https://doi.org/10.1109/JSEN.2017.2722819	SmartCitizen
4	Bannatyne, L.J., Rowntree, K.M., Van Der Waal, B.W., Nyamela, N., 2017. Design and implementation of a citizen technician based suspended sediment monitoring network: Lessons from the tsitsa river catchment, South Africa. Water SA 43, 365–377. https://doi.org/10.4314/wsa.v43i3.01	Open Data Kit
5	Bayas, J.C.L., See, L., Fritz, S., Sturn, T., Perger, C., Durauer, M., Karner, M., Moorthy, I., Schepaschenko, D., Domian, D., McCallum, I., 2016. Crowdsourcing in-situ data on land cover and land use using gamification and mobile technology. Remote Sensing 8. https://doi.org/10.3390/rs8110905	FotoQuest Austria
6	Becker, M., Caminiti, S., Fiorella, D., Francis, L., Gravino, P., Haklay, M., Hotho, A., Loreto, V., Mueller, J., Ricchiuti, F., Servedio, V.D.P., Sîrbu, A., Tria, F., 2013. Awareness and Learning in Participatory Noise Sensing. PLoS One 8. https://doi.org/10.1371/journal.pone.0081638	WideNoise
7	Bellfield, H., Sabogal, D., Goodman, L., Leggett, M., 2015. Case study report: Community-based monitoring systems for REDD+ in Guyana. Forests 6, 133–156. https://doi.org/10.3390/f6010133	Open Data Kit
8	Bocher, E., Petit, G., Picaut, J., Fortin, N., Guillaume, G., 2017. Collaborative noise data collected from smartphones. Data in Brief 14, 498–503. https://doi.org/10.1016/j.dib.2017.07.039	NoiseCapture
9	Boyce, M.S., Corrigan, R., 2017. Moose survey app for population monitoring. Wildlife Society Bulletin 41, 125–128. https://doi.org/10.1002/wsb.732	Moose Survey
10	Burr, D., Kline, J., Perryman, A., 2014. A smartphone application for monitoring gopher tortoises in Florida. Florida Scientist 77, 198–203.	Florida Gopher Tortoise
11	Busch, J.A., Bardaji, R., Ceccaroni, L., Friedrichs, A., Piera, J., Simon, C., Thijsse, P., Wernand, M., van der Woerd, H.J., Zielinski, O., van derWoerd, H.J., Zielinski, O., 2016. Citizen Bio-Optical Observations from Coastand Ocean and Their Compatibility with Ocean Colour Satellite Measurements. Remote Sensing, Remote Sens. (Switzerland) 8, 879 (19 pp.). https://doi.org/10.3390/rs8110879	EyeOnWater-Colour
12	Busch, J.A., Price, I., Jeansou, E., Zielinski, O., Woerd, H.J. der, 2016. Citizens and satellites: Assessment of phytoplankton dynamics in a NW Mediterranean aquaculture zone. International Journal of Applied Earth Observation and Geoinformation 47, 40–49. https://doi.org/10.1016/j.jag.2015.11.017	EyeOnWater
13	Calbimonte, J.-P., Eberle, J., Aberer, K., 2017. Toward Self-monitoring Smart Cities: the OpenSense2 Approach. Informatik-Spektrum 40, 75–87. https://doi.org/10.1007/s00287-016-1009-y	tinyGSN
14	Callaghan, C.T., J.M. Martin, R.E. Major, and R.T. Kingsford 2018. Avian monitoring – comparing structured and unstructured citizen science. Wildlife Research 45, 176–184.	eBird
15	Campanaro, A., Hardersen, S., Zan, L.R.D., Antonini, G., Bardiani, M., Maura, M., Maurizi, E., Mosconi, F., Zauli, A., Bologna, M.A., Roversi, P.F., Peverieri, G.S., Mason, F., 2017. Analyses of occurrence data of protected insect species collected by citizens in Italy. Nature Conservation 20, 265–297. https://doi.org/10.3897/natureconservation.20.12704	MIPP
16	Carpaneto, G.M., Campanaro, A., Hardersen, S., Audisio, P., Bologna, M.A., Roversi, P.F., Peverieri, G.S., Mason, F., 2017. The life project "monitoring of insects with public participation" (mipp): aims, methods and conclusions. Nature Conservation 20, 1–35. https://doi.org/10.3897/natureconservation.20.12761	MIPP
17	Confalonieri, R., M. Foi, R. Casa, S. Aquaro, E. Tona, M. Peterle, A. Boldini, G. De Carli, A. Ferrari, G. Finotto, T. Guarneri, V. Manzoni, E. Movedi, A. Nisoli, L. Paleari, I. Radici, M. Suardi, D. Veronesi, S. Bregaglio, G. Cappelli, M.E. Chiodini, P. Dominoni, C. Francone, N. Frasso, T. Strella, and M. Acutis. 2013. Development of an app for estimating leaf area index using a smartphone. Trueness and precision determination and comparison with other indirect methods. Computers and Electronics in Agriculture 96, 67–74.	PocketLAI
18	Connelly, N.A., Lauber, T.B., Niederdeppe, J., Knuth, B.A., 2018. Using a Web-Based Diary Method to Estimate Risks and Benefits from Fish Consumption. Risk Analysis 38, 1116–1127. https://doi.org/10.1111/risa.12925	
19	Craig, A., Moore, D., Knox, D., 2017. Experience sampling: Assessing urban soundscapes using in-situ participatory methods. Applied Acoustics 117, 227–235. https://doi.org/10.1016/j.apacoust.2016.05.026	Think About Sound
20	D'Hondt, E., Stevens, M., Jacobs, A., 2013. Participatory noise mapping works! An evaluation of participatory sensing as an alternative to standard techniques for environmental monitoring. Pervasive and Mobile Computing 9, 681–694. https://doi.org/10.1016/j.pmcj.2012.09.002	NoiseTube
21	Daum, T., H. Buchwald, A. Gerlicher, and R. Bimer 2018. Smartphone apps as a new method to collect data on smallholder farming systems in the digital age: A case study from Zambia. Computers and Electronics in Agriculture 153, 144–150.	Time-Tracker
22	Davis, A., Major, R.E., Taylor, C.E., Martin, J.M., 2017. Novel tracking and reporting methods for studying large birds in urban landscapes. WILDLIFE BIOLOGY. https://doi.org/10.2981/wlb.00307	Wingtags
23	Dellinger, M.J., Olson, J., Clark, R., Pingatore, N., Ripley, M.P., 2018. Development and pilot testing of a model to translate risk assessment data for Great Lakes Native American communities using mobile technology. Human and Ecological Risk Assessment 24, 242–255. https://doi.org/10.1080/10807039.2017.1377596	Gigiigoo'inaan [Our Fish]
24	DeVries, B., Pratihast, A.K., Verbesselt, J., Kooistra, L., Herold, M., 2016. Characterizing Forest Change Using Community-Based Monitoring Data and Landsat Time Series. PLoS One 11. https://doi.org/10.1371/journal.pone.0147121	Open Data Kit
25	Ferster, C.J., Coops, N.C., Harshaw, H.W., Kozak, R.A., Meitner, M.J., 2013. An Exploratory Assessment of a Smartphone Application for Public Participation in Forest Fuels Measurement in the Wildland-Urban Interface. FORESTS 4, 1199–1219. https://doi.org/10.3390/f4041199	ForestFuels
26	Ferster, C.J. and N.C. Coops. 2014. Integrating volunteered smartphone data with multispectral remote sensing to estimate forest fuels. International Journal of Digital Earth 19(2), 171–196.	ForestFuels
27	Francone, C., V. Pagani, M. Foi, G. Cappelli, and R. Confalonieri. 2014. Comparison of leaf area index estimates by ceptometer and PocketLAI smart app in canopies with different structures. Field Crops Research 155, 38–41.	PocketLAI
28	Friedrichs, A., Busch, J.A., van der Woerd, H.J., Zielinski, O., 2017. SmartFluo: A method and affordable adapter to measure chlorophyll *a* fluorescence with smartphones. Sensors (Switzerland) 17. https://doi.org/10.3390/s17040678	SmartFluo-APP

(*continued on next page*)

Table 2 (*continued*)

	Citation	Related apps
29	Golumbeanu, M., Nenciu, M., Galatchi, M., Nita, V., Anton, E., Oros, A., Ioakeimidis, C., Belchior, C., 2017. Marine litter watch App as a tool for ecological education and awareness raising along the Romanian Black Sea coast. Journal of Environmental Protection and Ecology 18, 348–362.	Marine Litter Watch
30	Guillaume, G., Can, A., Petit, G., Fortin, N., Palominos, S., Gauvreau, B., Bocher, E., Picaut, J., 2016. Noise mapping based on participative measurements. Noise Mapping 3, 140–156. https://doi.org/10.1515/noise-2016-0011	OnoM@p
31	Hann, C.H., Stelle, L.L., Szabo, A., Torres, L.G., 2018. Obstacles and opportunities of using a mobile app for marine mammal research. ISPRS International Journal of Geo-Information 7, 169 (18 pp.)-169 (18 pp.). https://doi.org/10.3390/ijgi7050169	Whale mAPP
32	Hawthorne, T.L., Elmore, V., Strong, A., Bennett-Martin, P., Finnie, J., Parkman, J., Harris, T., Singh, J., Edwards, L., Reed, J., 2015. Mapping non-native invasive species and accessibility in an urban forest: A case study of participatory mapping and citizen science in Atlanta, Georgia. Applied Geography 56, 187–198. https://doi.org/10.1016/j.apgeog.2014.10.005	ESRI ArcGIS
33	Heigl, F., Horvath, K., Laaha, G., Zaller, J.G., 2017. Amphibian and reptile road-kills on tertiary roads in relation to landscape structure: Using a citizen science approach with open-access land cover data. BMC Ecology 17. https://doi.org/10.1186/s12898-017-0134-z	SPOTTERON Roadkill
34	Herrick, J.E., Karl, J.W., McCord, S.E., Buenemann, M., Riginos, C., Courtright, E., Van Zee, J., Ganguli, A.C., Angerer, J., Brown, J.R., Kimiti, D.W., Saltzman, R., Beh, A., Bestelmeyer, B., 2017. Two New Mobile Apps for Rangeland Inventory and Monitoring by Landowners and Land Managers. Rangelands 39, 46–55. https://doi.org/10.1016/j.rala.2016.12.003	LandInfo, LandCover
35	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 Platform to Facilitate the Collection of Citizen Science data for Environmental Monitoring. INTERNATIONAL JOURNAL OF SPATIAL DATA INFRASTRUCTURES RESEARCH 11, 20–48. https://doi.org/10.2902/1725-0463.2016.11.art3	
36	Idris, N.H., Osman, M.J., Kanniah, K.D., Idris, N.H., Ishak, M.H.I., 2017. Engaging indigenous people as geo-crowdsourcing sensors for ecotourism mapping via mobile data collection: a case study of the Royal Belum State Park. Cartography and Geographic Information Science 44, 113–127. https://doi.org/10.1080/15230406.2016.1195285	
37	Jelks, N.O., Hawthorne, T.L., Dai, D., Fuller, C.H., Stauber, C., 2018. Mapping the hidden hazards: Community-led spatial data collection of street-level environmental stressors in a degraded, urban watershed. International Journal of Environmental Research and Public Health 15. https://doi.org/10.3390/ijerph15040825	ESRI ArcGIS (Proctor Creek Citizen Science Application)
38	Kangas, A., Rasinmaki, J., Eyvindson, K., Chambers, P., 2015. A Mobile Phone Application for the Collection of Opinion Data for Forest Planning Purposes. Environmental Management 55, 961–971. https://doi.org/10.1007/s00267-014-0438-0	Tienoo
39	Kress, W.J., Garcia-Robledo, C., Soares, J.V.B., Jacobs, D., Wilson, K., Lopez, I.C., Belhumeur, P.N., 2018. Citizen Science and Climate Change: Mapping the Range Expansions of Native and Exotic Plants with the Mobile App Leafsnap. BioScience 68, 348–358. https://doi.org/10.1093/biosci/biy019	Leafsnap
40	Kumar, R., Mukherjee, A., Singh, V.P., 2017. Traffic noise mapping of Indian roads through smartphone user community participation. Environmental Monitoring and Assessment 189. https://doi.org/10.1007/s10661-016-5741-1	Google Maps
41	Lagoze, C. 2014. eBird: Curating citizen science data for use by diverse communities. International Journal of Digital Curation 9(1), 71–82.	eBird
42	Land-Zandstra, A.M., Devilee, J.L.A., Snik, F., Buurmeijer, F., van den Broek, J.M., 2016. Citizen science on a smartphone: Participants' motivations and learning. Public Understanding of Science 25, 45.	iSPEX
43	Leeuw, T. and E. Boss. 2018. The HydroColor app: Above water measurements of remote sensing reflectance and turbidity using a smartphone camera. Sensors 18, 256.	HydroColor
44	Liebenberg, L., Steventon, J., Brahman, !Nate, Benadie, K., Minye, J., Langwane, H. (Karoha), Xhukwe, Q. (Uase), 2017. Smartphone Icon User Interface design for non-literate trackers and its implications for an inclusive citizen science. Biological Conservation 208, 155–162. https://doi.org/10.1016/j.biocon.2016.04.033	CyberTracker
45	Linnap, M. and Rice, A., 2014. Managed Participatory Sensing with YouSense. Journal of Urban Technology 21, 9–26. https://doi.org/10.1080/10630732.2014.888216	YouSense
46	Maezawa, Y., Hatakeyama, Y., Saito, M., Hirota, F., 2014. Conservation of biodiversity by making use of ICT. Fujitsu Scientific and Technical Journal 50, 44–51.	
47	Maisonneuve, N., Stevens, M., Ochab, B., 2010. Participatory noise pollution monitoring using mobile phones. Information Polity 15, 51–71. https://doi.org/10.3233/IP-2010-0200	NoiseTube
48	Marchante, H., Morais, M.C., Gamela, A., Marchante, E., 2017. Using a WebMapping Platform to Engage Volunteers to Collect Data on Invasive Plants Distribution. Transactions in GIS 21, 238–252. https://doi.org/10.1111/tgis.12198	WebMapping
49	Marx, S., Hämmerle, M., Klonner, C., Höfle, B., 2016. 3D Participatory Sensing with Low-Cost Mobile Devices for Crop Height Assessment – A Comparison with Terrestrial Laser Scanning Data. PLoS One 11. https://doi.org/10.1371/journal.pone.0152839	Open Data Kit
50	Merlin, S., Locritani, M., Stroobant, M., Mioni, E., Tosi, D., 2015. SeaCleaner: Focusing Citizen Science and Environment Education on Unraveling the Marine Litter Problem. MARINE TECHNOLOGY SOCIETY JOURNAL 49, 99–118. https://doi.org/10.4031/MTSJ.49.4.3	SeaCleaner
51	Naykki, T., Koponen, S., Vaisanen, T., Pyhalahti, T., Toivanen, T., Leito, I., 2014. Validation of a new measuring system for water turbidity field measurements. Accreditation and Quality Assurance 19, 175–183. https://doi.org/10.1007/s00769-014-1052-9	
52	Olson, D.D., J.A. Bissonette, P.C. Cramer, A.D. Green, S.T. Davis, P.J. Jackson, and D.C. Coster. 2014. Monitoring wildlife-vehicle collisions in the information age: How smartphones can improve data collection. PLOS ONE 9(6), e98613.	Wildlife-Vehicle Collision Reporter
53	Olyazadeh, R., Sudmeier-Rieux, K., Jaboyedoff, M., Derron, M.-H., Devkota, S., 2017. An offline–online Web-GIS Android application for fast data acquisition of landslide hazard and risk. Natural Hazards and Earth System Sciences 17, 549–561. https://doi.org/10.5194/nhess-17-549-2017	ROOMA (Rapid Offline–Online Mapping Application)
54	Oviedo, A.F.P., Bursztyn, M., 2017. Community-based monitoring of small-scale fisheries with digital devices in Brazilian Amazon. Fisheries Management and Ecology 24, 320–329. https://doi.org/10.1111/fme.12231	Open Data Kit
55	Paul, S.A.L., Wilson, A.M.W., Cachimo, R., Riddell, M.A., 2016. Piloting participatory smartphone mapping of intertidal fishing grounds and resources in northern Mozambique: Opportunities and future directions. Ocean and Coastal Management, Ocean Coast. Manag. (Netherlands) 134, 79–92. https://doi.org/10.1016/j.ocecoaman.2016.09.018	CyberTracker
56	Pratihast, A.K., Herold, M., Avitabile, V., de Bruin, S., Bartholomeus, H., Souza, C.M., Ribbe, L., 2013. Mobile devices for community-based REDD+ monitoring: a case study for central Vietnam. Sensors, Sensors (Switzerland) 13, 21–38. https://doi.org/10.3390/s130100021	Open Data Kit

(*continued on next page*)

Table 2 (*continued*)

	Citation	Related apps
57	Rana, R., Chou, C.T., Bulusu, N., Kanhere, S., Hu, W., 2015. Ear-Phone: A context-aware noise mapping using smart phones. Pervasive and Mobile Computing 17, 1–22. https://doi.org/10.1016/j.pmcj.2014.02.001	Ear-Phone
58	Scanlon, E., Woods, W., Clow, D., 2014. Informal Participation in Science in the UK: Identification, Location and Mobility with iSpot. Educational Technology & Society 17, 58–71.	iSpot
59	Seafarers, S.D., Lavender, S., Beaugrand, G., Outram, N., Barlow, N., Crotty, D., Evans, J., Kirby, R., 2017. Seafarer citizen scientist ocean transparency data as a resource for phytoplankton and climate research. PLoS One 12. https://doi.org/10.1371/journal.pone.0186092	Secchi
60	Snik, F., Rietjens, J.H.H., Apituley, A., Volten, H., Mijling, B., Di Noia, A., Heikamp, S., Heinsbroek, R.C., Hasekamp, O.P., Smit, J.M., Vonk, J., Stam, D.M., Van Harten, G., De Boer, J., Keller, C.U., 2014. Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. Geophysical Research Letters 41, 7351–7358. https://doi.org/10.1002/2014GL061462	iSpex
61	Steen, R., 2017. Bird monitoring using the smartphone (iOS) application Videography for motion detection. Bird Study 64, 62–69. https://doi.org/10.1080/00063657.2016.1271772	Videography
62	Storer, J., Chao, J., Torelli, A., Ostrowski, A., 2016. KnoWare: A system for citizen-based environmental monitoring. Informing Science 19, 125–139.	KnoWare, InSpector
63	Sullivan, B.L., J.L. Aycrigg, J.H. Barry, R.E. Bonney, N. Bruns, C.B. Cooper, T. Damoulas, A.A. Dhondt, T. Dietterich, A. Farnsworth, D. Fink, J.W. Fitzpatrick, T. Fredericks, J. Gerbracht, C. Gomes, W.M. Hochachka, M.J. Iliff, C. Lagoze, F.A. La Sorte, M. Merrifield, W. Morris, T.B. Phillips, M. Reynolds, A.D. Rodewald, K.V. Rosenberg, N.M. Trautmann, A. Wiggins, D.W. Winkler, W.-K. Wong, C.L. Wood, J. Yu and S. Kelling. 2014. The eBird enterprise: An integrated approach to development and application of citizen science. Biological Conservation 169, 31–40.	eBird
64	Vercayie, D., Herremans, M., 2015. Citizen science and smartphones take roadkill monitoring to the next level. Nature Conservation 11, 29–40. https://doi.org/10.3897/natureconservation.11.4439	ObsMapp, iObs, WinObs
65	Wang, C., Qiao, Y., Wu, H., Chang, Y., Shi, M., 2016. Empowering fall webworm surveillance with mobile phone-based community monitoring: a case study in northern China. Journal of Forestry Research 27, 1407–1414. https://doi.org/10.1007/s11676-016-0230-5	Open Data Kit
66	Yang, Y., Cowen, L.L.E., Costa, M., 2018. Is ocean reflectance acquired by citizen scientists robust for science applications? Remote Sensing 10. https://doi.org/10.3390/rs10060835	HydroColor
67	Yu, Q., Shi, Y., Tang, H., Yang, P., Xie, A., Liu, B., Wu, W., 2017. eFarm: A tool for better observing agricultural land systems. Sensors (Switzerland) 17. https://doi.org/10.3390/s17030453	eFarm
68	Zamora, W., Calafate, C.T., Cano, J.-C., Manzoni, P., 2017. Accurate ambient noise assessment using smartphones. Sensors (Switzerland) 17. https://doi.org/10.3390/s17040917	
69	Zapponi, L., Cini, A., Bardiani, M., Hardersen, S., Maura, M., Maurizi, E., Redolfi De Zan, L., Audisio, P., Bologna, M.A., Carpaneto, G.M., Roversi, P.F., Sabbatini Peverieri, G., Mason, F., Campanaro, A., 2017. Citizen science data as an efficient tool for mapping protected saproxylic beetles. Biological Conservation 208, 139–145. https://doi.org/10.1016/j.biocon.2016.04.035	MIPP
70	Zheng, H., Hong, Y., Long, D., Jing, H., 2017. Monitoring surface water quality using social media in the context of citizen science. Hydrology and Earth System Sciences 21, 949–961. https://doi.org/10.5194/hess-21-949-2017	WeChat (Tsinghua Environment Monitoring Platform)
71	Zilli, D., Parson, O., Merrett, G. V, Rogers, A., 2014. A Hidden Markov Model-Based Acoustic Cicada Detector for Crowdsourced Smartphone Biodiversity Monitoring. Journal of Artificial Intelligence Research 51, 805–827.	Cicada Hunt

3.1. Key characteristics of the literature

A total of 2876 papers were screened for relevance, with a final 71 papers selected for analysis (Fig. 1). Table 2 contains a full list of articles in our analysis and the names of focal apps within each paper. The oldest paper in our analysis was from 2010, with a trend of increasingly more publications (Fig. 2), which speaks to how this is an emerging area of research and interest. Note that our search was conducted in July 2018, which influences the number of publications reviewed from that year and beyond. All papers involved the use of a smartphone app and some also included the use of a tethered device (attached to a smartphone with a wire or through wireless technology). The geographic distribution of where the apps were deployed was 37% in Europe, 20% in North America, 10% in Asia, 8% in Africa, 1% in South

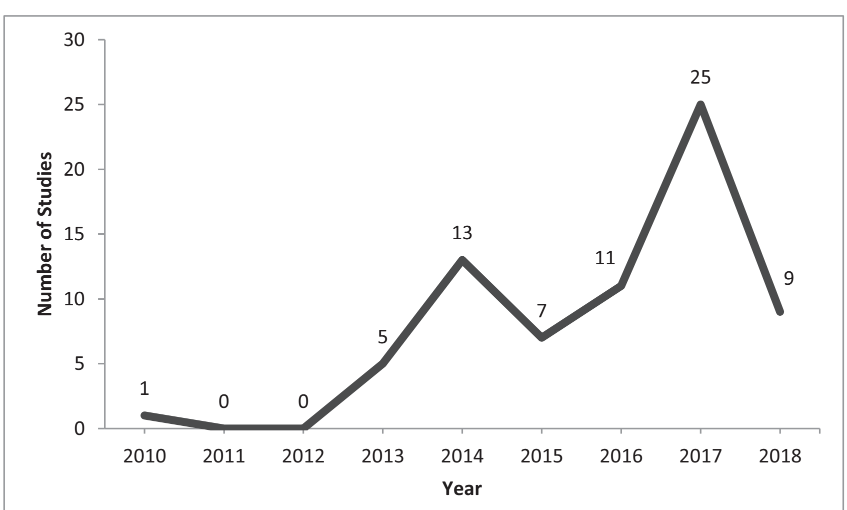

Fig. 2. Number of peer-reviewed studies included in analysis, by year (total n = 71). The search was performed mid-2018.

America, 1% in Australia, and 23% had no specific focus. In terms of the intended scale of use, 52% of the apps were for local use, 15% were for national use, and 32% were for international use. Scale is important to consider because not all apps were designed or intended for widespread use. Among the apps intended for local use, these apps targeted a specific local community, local landscape or ecosystem, or interest group (e.g., birders, anglers, or pastoralists). This has important implications for the amount of data that may be collected through these technologies: not all apps involve 'big data'.

Across the literature a range of benefits were identified for using smartphone technology in environmental monitoring. Two of the most commonly assumed benefits were cost effectiveness and wider geographic coverage. Costs were often described in comparison to the expenses required for monitoring programs that involve extensive field hours for trained experts or that use sophisticated, specialized equipment. Authors frequently stated or implied that with widespread ownership of smartphones, the general public has the ability to participate in monitoring with relatively little investment on the part of the researchers or monitoring programs. Broad geographic coverage was believed to be possible also because of the ubiquity of smartphones. The assumption was that the general public (citizen scientists) will be able to collectively cover more areas including remote regions or private lands.

Related to the ubiquity of smartphones, authors espoused the potential to enable larger sample sizes, provide rapid and real time sensing, and help fill data gaps. Other assumed benefits included statements about objectivity of sensors, ground truthing, integration of multiple data types, easier public engagement, raising awareness of environmental issues, empowerment of local communities, and ability to share information and results. Identifying these assumptions about benefits are important because they were rarely examined or tested in the literature, as we highlight below.

3.2. Data collection and handling

Across the literature there were some notable tendencies related to what was being monitored, who was doing the monitoring, and how observations were recorded. A broad variety of biotic and abiotic conditions were monitored (Fig. 3). While there was a range of topics of interest, nearly half (44%) were related to biodiversity and wildlife. There were several instances of passive or automated data collection but most apps required active operation by users. Many apps involved data collection from multiple sensors built into smartphones (51%). For instance, use of GPS sensing can be combined with built in cameras, and this can be extended to include accelerometers, time of day, and even qualitative observations. Other forms of data entry included manual text or data entry (28%), built in camera (11%), built in microphone (7%), or an attached device (3%).

With respect to who were the intended users of the apps, over two-thirds of the papers (70%) were focusing on citizen scientists or the general public. Other intended users of the apps included specific geographic communities (13%), interest groups (13%), or employees or volunteers from a specific organization (4%). The propensity to rely on volunteers brings issues around privacy and ethics to the forefront. Central among privacy issues is the short and long term ownership, transmission, and storage of data. Surprisingly, 58% of the papers did not acknowledge who has access to data collected through smartphones, let alone report on engagement with agencies who could ultimately make use of the environmental data generated. Given that much of this research is publicly funded and relies on volunteers there are strong calls within the citizen science community for open access (e.g., Groom et al., 2017; Luna et al., 2018; Williams et al., 2018), yet we do not see clear indication in the literature of whether or not this is standard practice.

3.3. The app development process

Decisions made during the development of an app (and related technologies) can influence the level of engagement and buy-in on a project and future compatibility of technologies. It is notable that 72% of the studies we reviewed were reporting on apps that were deployed by university-based researchers. Furthermore, 68% of all studies involved the creation of unique apps, as opposed the use of third party apps (7%) or tailored apps built on third party platforms (18%). These numbers suggest that scholars have been more intent on devising their own projects and technologies, compared to investigating how non-academic projects are making use of apps for environmental monitoring. A concerning observation was that in only 15% of the studies were the intended end users of the apps consulted during app development. In another 15% of the studies we were not able to determine if

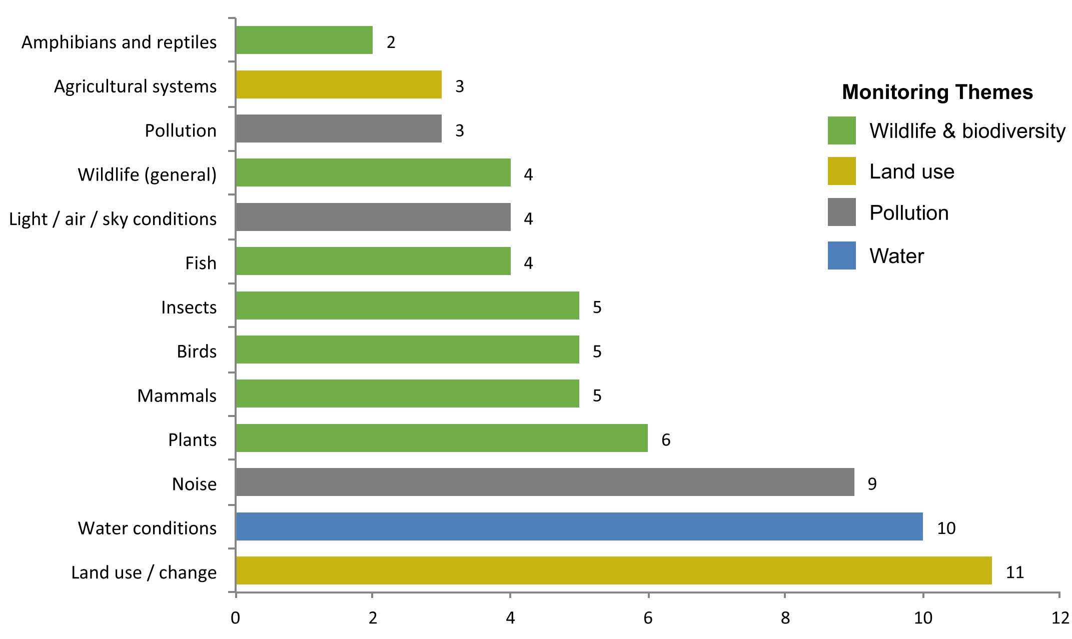

Fig. 3. Summary of types of environmental conditions being monitored (total n = 71). Of all apps, 44% related to wildlife and biodiversity.

end users were consulted, while in the remaining 69% of the studies the end users were not consulted. While some of these studies were focused on technical aspects of innovation, the level of separation from end users may be a concern.

The literature showed a strong preference for Android and Apple iOS operating systems. Android was used in 30% of the studies, Apple iOS was used in 10% of the studies, and 54% of the studies used multiple operating systems (which virtually always included Android and iOS). In 7% of the studies we were not able to identify the operating system. Across the literature, software and hardware compatibility issues were rarely mentioned. However, among studies that made use of third party platforms for tailoring apps (e.g., Open Data Kit or ESRI's Arc GIS application), authors noted the value of receiving automatic software updates, enabling participation from owners of different types of phones, and not requiring expertise in computer science to create an app. Other topics that came up in the papers included battery life and addressing connectivity limitations in rural areas.

3.4. Reporting on research outcomes

What then does the literature note in terms of whether smartphone-based environmental monitoring is influencing research, policy, and practice? Statements about such research outcomes were highly speculative, with much of the literature merely re-iterating assumed benefits and offering a proof of concept but not studying real-world uptake of data or outcomes. Authors remain optimistic about the promise of smartphone technologies for environmental monitoring (one-fifth of the studies did not report any limitations of using smartphones for environmental monitoring) but commentary on the actual uptake and use of generated data were often prefaced with modifiers such as “may”, “could”, “might”, “possible”, or “potential”. To illustrate the use of such modifiers: “Experimental results show that, if the smartphone application is well tuned, it is possible to measure noise levels with a accuracy [sic] degree comparable to professional devices” (Table 2: Zamora et al., 2001, p.1).

That noted, nearly half (45%) of the studies' main objective was to investigate the performance of an app in comparison to conventional monitoring methods (e.g., validation or calibration of a tool) rather than evaluating actual impacts. Further, 41% of the studies involved only a rationale and description of an app and related technologies (e.g., a tethered device designed for specialized observations), 10% analysed data collected through an app, and 4% investigated how people used an app. In sum, the literature as a whole has not been concerned with evaluating actual impacts or outcomes from data generation.

For the few studies that evaluated how people use and interact with apps, there were inferences about the benefits of smartphones for community engagement. For instance, several papers described direct benefits to app users that included learning about environmental issues, opportunities to interact with other app users (i.e., people who share similar interests or concerns), and empowerment by having a role in the process of environmental monitoring. There is evidence to suggest that, by stimulating app-based discussions and providing educational materials, smartphones hold unique promise as a tool for engaging interest groups. One way that this has taken shape is when an app provides a service that people are already interested in. The eBird app is a prime example where birders' interests in the ability to track their birding lists have been key for uptake. That people are helping to generate data for research and conservation is an indirect, beneficial output. Another way that interest groups have been highly engaged is through direct feedback from the data that users generate. This often takes the form of maps or graphs generated as users add more data points, or can also combine data entries with external information to provide users with information that is useful to their own wellbeing (e.g., information on healthy levels of fish consumption).

Several papers revealed how reliance on citizen scientists created biases in data collection that need to be accounted for. For instance, because citizen scientists tend to be opportunistic and collect data when it is most convenient for themselves, the data they generate can have a tendency to highlight exceptions rather than generalizable patterns. This is in line with findings from the citizen science literature (e.g., Callaghan et al., 2017; Sullivan et al., 2017). For noise sensing apps this may mean that more data is collected in especially busy and loud locales, for birding apps this may surface as entries of rare species that users sought out, or for pollution documentation apps this may result as users go to areas known as highly polluted. In terms of useful outcomes, these types of data can be highly advantageous for drawing attention to places and issues in most need of attention. The onus falls on researchers and other users of data to understand how data is collected and to carefully interpret findings.

4. Discussion

The aim of this systematic review was to examine the current state of knowledge and trends in the peer-reviewed literature related to the use of smartphone technologies for environmental monitoring. Our analysis reveals tendencies towards testing proof of concepts for software (apps) and hardware (sensors) innovations. There was also some separation from researchers and the people who are presumed to employ those technologies and ultimately benefit from them. Below we identify two key challenges and discuss them with an eye towards inviting conservation scholars and practitioners to address them together (Toomey et al., 2017). We also offer a set of recommendations for improved research on the use of smartphones to support effective and equitable conservation.

4.1. The cost paradox

Given the ubiquity of statements in the literature about the cost effectiveness of employing smartphones for environmental monitoring, actual costs were rarely calculated or tested. Only three papers (Table 2: Hann et al., 2019; Heigl et al., 2017; Pratihast et al., 2013) attempted calculations of costs or considered comparisons with alternative means of monitoring. These papers at least offered some level of validation of the cost-effectiveness of smartphone-based environmental monitoring. Citizen science scholars have noted that although citizen science draws on volunteer contributions, it is not free (Sauermann and Franzoni, 2015; Blaney et al., 2016). Costs can include administration and staffing, website development, data storage, and participant recruitment. Distinct costs associated with smartphone-based monitoring are not being addressed or even acknowledged in the vast majority of literature. We call this problem the cost paradox.

Start-up costs for developing new sensors and apps require, in the context of university-based programs, research funding. Aside from salary for faculty, graduate students, and research staff, expenses include outreach to recruit participants, setting up and hosting databases, distributing apps (e.g., if an app is to be made publicly available there are recurring fees for making it available in Google or Apple's app stores), and eventual analysis and interpretation of data. As threats to digital security are part of our new online reality (viruses, hackers) and technological improvements require frequent updating for compatibility, there are inevitable costs for ongoing supervision and maintenance of smartphone technologies. Wiggins (2013) noted that lack of adequate funding can result in suboptimal digital tools and that unanticipated costs can arise due to poor functionality. There are also notoriously low prospects for adoption and retention rates for new apps, meaning that all of this investment into app development may not lead to success. The general expectation among citizen science researchers is that a few participants will contribute large amounts of data, while the majority of participants contribute once or infrequently (Cooper et al., 2017).

There are context-specific cost-benefit balances depending on what is being monitored and how those elements have conventionally been monitored. One paper developed a spectropolarimeter to monitor atmospheric aerosols as a supplement to conventional monitoring that can include the use of satellites (Table 2: Snik et al., 2014). Another paper created an app to provide an inland indigenous fishery with calculations of contaminant concentrations and tailored fish consumption advisories (Table 2: Dellinger et al., 2018). The cost-benefit comparisons for these two cases are quite different but neither documented the extent of short and long term demands on staffing, volunteers, technological upgrades, and other expenses. It is also noteworthy that many organizations are recently choosing to use popular apps such as iNaturalist and eBird instead of developing their own apps. For end-users and researchers, there are numerous up-front cost savings by creating projects within these (and other) freely available apps. In terms of contributions to conservation science, these large internationally available platforms are generating increasingly more research grade data. Unfortunately for our literature review, many peer reviewed papers that draw on these data do not adequately mention or describe the role of smartphones and apps in the data collection process. Rather, they noted data sources and moved into their analyses.

There are also important considerations related to power and equity. We did not see acknowledgement of monetary costs for smartphone owners (for the phones themselves and data plans) or the opportunity costs for people volunteering their time. In spite of global expansion of the internet and communication technologies, inequalities persist in terms of access and use of devices, affordability and quality of technologies, connectivity in rural and remote areas, and educational and literacy barriers (Graham, 2011; Haklay, 2013; Weiss et al., 2015, 2016). These critical economic, racial, political, and geographic discrepancies are sometimes referred to as digital divides (Dewan and Riggins, 2005; Sui et al., 2012; Weiss et al., 2016). Within communities, there tend to be differences in who can afford smartphones and who can afford to volunteer their time. These issues affect where data is collected, who is collecting the data, and hence whose views are represented. We need to think holistically about how people experience and participate in monitoring projects, including who is making decisions about monitoring objectives and whether smartphone technologies are locally appropriate tools. We should not be accepting statements about low costs and affordability of smartphone-based environmental monitoring at face value. While at least some of the costs for monitoring are displaced from researchers, we need studies that are more transparent about who is bearing different types of costs and what the implications are for monitoring.

4.2. People and partnerships as key ingredients

A striking aspect of our review was the promise of apps compared with the reality of documenting outcomes from data collection or from people being actively engaged and learning. Less evidence of engagement was present than predicated. As we reported, many papers did not fully engage with or reflect on the people who would use the smartphone technologies (69% of papers not consulting users during app development). This is a lost opportunity to work with interest groups or local communities who are purported to have key roles as data collectors, and who often will be most affected by environmental management initiatives. To take this argument further, the absence of participant engagement is the antithesis of community-driven research, where research questions and methods are defined by communities (or community groups) in order for historically marginalized groups to reclaim control over their knowledge and representation (Smith, 1999; Heaney et al., 2007).

The literature in our analysis did not demonstrate an understanding of the motivation of potential users and their preferences for how to interact with the technologies. This level of separation from end users is a concern. As we noted earlier, there is a sizable literature on participant engagement, including a recent systematic review by Skarlatidou et al. (2019) that contributes to our understanding of user experiences with citizen science technologies and proposes best practice guidelines. Researchers considering developing new apps or making use of existing apps need to draw on these existing resources and insights, whether they are interested in community-driven research or large platform-based contributory research.

One premise of our review was to synthesize an understanding of how the use of smartphone technologies is helping address pressing environmental and conservation challenges. Few studies in our review reported on actual outcomes or impacts in using smartphones for monitoring programs, focusing on proposed or hopeful outcomes rather than established projects that have a track record of impacts. In line with our findings, Sullivan et al. (2017) observed that it is rare to see documentation of contributions from data collected via app-based citizen science to conservation, and Edwards et al. (2018) found that levels of engagement and learning do not always match the aspirations of citizen science projects. A caveat here is that many of the studies we reviewed are likely reporting on the early stages of projects, whereas papers from the latter stages of projects may focus more on outcomes but not technical details of data collection. We do note that there is literature that has documented examples of the ability of smartphones and other digital platforms to cultivate connections to nature (Sharma et al., 2019), promote learning in formal and informal education settings (Bonney et al., 2016; NASEM, 2018), and contribute to policy and decision-making (Nascimento et al., 2018; Owen and Parker, 2018). Valuable efforts have commenced to evaluate conservation outcomes of citizen science projects (e.g., Conrad and Hilchey, 2011; Ballard et al., 2017; McKinley et al., 2017; Sullivan et al., 2017; Ballard et al., 2018). More of this type of research is needed, especially with respect to the functions and influences of smartphones.

Spiers et al. (2019) found that when designing digital elements of citizen science projects there are trade-offs between optimizing for scientific precision versus community engagement. Our review uncovered the infrequent consideration of all actors who play a role in science, policy, and action: those who create and deploy the smartphone-based technologies, those who act as sensors and collect data, and those who will ultimately make use of results to inform practice and policy (notwithstanding overlap among these groupings). The balance of literature we analysed paid much more attention to scientific precision than engagement of communities or policy actors.

We concur with Brammer et al.'s (2016) finding that digital data entry may detract from monitoring objectives if appropriate partnerships and collaborations are not present. The essence here is that people and partnerships – formal or informal – are central ingredients to ensure that research outcomes contribute to policy and action (Cvitanovic et al., 2015; Cairney and Oliver, 2018). While there is plenty of optimism around the potential for digital technologies to improve flow of information, simply creating the technologies does not resolve persistent challenges of moving from data collection on apps to meaningful outcomes for public engagement and decision-making (Pimm et al., 2015). Matters of access to data are closely intertwined here too. We still need appropriate analysis and interpretation of data. We still need links to decision-making and public and political will to create policies, provide funding, and take action (Conrad, 2006; Wilson et al., 2018). We challenge scholars to see beyond the allure of innovative technologies and to ask more questions about whether and how smartphone technologies add meaningful human interactions, advance scientific understanding of environmental challenges, and ultimately have real world benefits.

4.3. Recommendations for research

We offer several recommendations for research in this field. First, we need more cost-benefit assessments that investigate the extent of tangible impacts on environmental monitoring and management objectives. Investigation of impacts would help inform when and how smartphone technologies can be effectively leveraged to contribute to natural resource management and ecological conservation. Such research would offer a critical inquiry into conditions that are conducive for education, engagement, and usable data. Investigation of costs should include engagement with app software developers to uncover key challenges and the actual time involved to build and maintain apps. We suspect that the costs of maintaining apps is highly underappreciated and underestimated (e.g., to refine functionality, address bugs, and update software to match operating system and hardware updates).

Our second recommendation is for more investigation of what makes an app successful (where success is internally defined by monitoring projects and programs, according to their goals). Are there trends across successful apps than can help us to better understand conditions that are best suited for environmental monitoring? Further documentation of failures is also important, and critical self-examination has been argued by Catalano et al. (2018) as a powerful learning opportunity. In this regard, Cornell (2017) offered an insightful account into good intentions and pitfalls of developing an app from scratch.

Third, more research is needed on how digital divides (geographical, economic, cultural, racial) influence who is and is not participating in environmental monitoring programs that involve smartphones. Included in such research should be considerations to differential privilege, experience, and learning abilities that influence inclusivity (e.g., Peltola and Arpin, 2018). Although we know digital divides exist, we need a better understanding of how participation inequality impacts data coverage, management priorities, and conservation outcomes. We need research that looks deeper into how digital divides are unfolding and how to meaningfully counter these processes – and we need to accept that the answer may be to eschew the use of smartphone technologies.

5. Conclusion

The future of environmental monitoring with smartphones is inherently unpredictable. Technological innovations will continue to drive what will be possible. Some of the anticipated advances might include expansion of real time and networked communication (Newman et al., 2012; Charriere and Bogaard, 2016), new tools for visualization and presentation of data (Chapron, 2015), use of in-app videos for training or sharing information (Starr et al., 2014), and application of augmented reality (Dorward et al., 2017). Yet, if these new technologies are to have meaningful impacts for environmental monitoring we need a more fulsome understanding of what environmental monitoring with smartphones is already accomplishing.

The effectiveness of smartphone technologies as a foundation to improve community-based and citizen-based environmental monitoring is not clear. As noted, guiding principles are emerging and offer important insights on the design and implementation of smartphone technology approaches. Yet, there remains a need to critically evaluate the extent that these technologies are meaningfully contributing to conservation efforts by engaging people or facilitating collection of monitoring data. By focusing this systematic review on empirical work and case studies we help shed light on the extent of evidence of real impacts and offer insights on needs for future research. The intent is not to call into question the impacts of smartphone technologies, but to encourage further understanding of how and when they can be most useful.

Acknowledgements

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Appendix A. Inclusion and exclusion criteria for literature search

Inclusion criteria	Exclusion criteria
English.	Not published in English.
Peer-reviewed primary research.	Thesis, dissertation, book, media, grey literature, conference proceeding, commentary, editorial, review, synthesis.
Monitoring of wildlife or environment broadly (any form of monitoring, surveillance, or observations of animals, plants, water, or other environmental conditions).	Article does not address monitoring of wildlife or environment (e.g. article is about conservation but not monitoring).
Focus is on monitoring at the community or local level.	Focus is on remote sensing or has a larger geographic focus that is regional, national or global.
Monitoring incorporates smartphones for recording observations (built in sensors (GPS, accelerometer, microphone, cameras), cell phone services, or pairing with other devices via wire or Bluetooth).	Monitoring does not involve phones or other mobile devices.

Appendix B. Questionnaire used to gather information about each paper

	Question	Description
1	What is the geographic focus of the app?	• North America • South America • Europe • Africa • Asia • Australia • Antarctic • Global/no specific focus
2	What is the scope of app use?	• Local • National • International
3	What is the year of publication?	• 2018 • 2017 • 2016 • …
4	Who deployed the app?	• NGO/nonprofit • Conservation project

		• Government • University/research • Other organization
5	Were end users consulted in app development?	• Yes • No
6	How was the app developed?	• Use of third party app • Use of third party platform for tailoring app • Unique app developed for project • No mention of app development
7	What is being monitored?	• Birds • Amphibians and reptiles • Mammals • Insects • Light/air/sky conditions • Noise • Water conditions • Pollution • Land use/change • Plants • Fish and fisheries • Wildlife (general) • Agricultural systems
8	What mobile operating system was used?	• Android • iOS/iPhone • Blackberry • Multiple platforms • Other/don't know
9	What is the mechanism of data collection?	• Built in camera • Built in microphone • Built in GPS • Built in accelerometer • Manual text entry and/or responding in forms • Attached device • Multiple built in sensors
10	Who is involved in environmental monitoring (app users)?	• Citizen scientists • Target geographic community/communities • Target population groups (e.g. farmers, pastoralists) • Employees, volunteers of a specific organization • Employees, volunteers of a specific project
11	How is app incorporated into the paper?	• Analysed data from an app • Rationale and description of an app • Investigation of app performance • Investigation of how people use app
12	Did the paper acknowledge who has access to the data?	• Yes • No • Don't know
13	What limitations were acknowledged in the paper?	• No limitations reported • User engagement • Costs • Time • Technical expertise to support app • Trust • Reliability of data • Training for app users

References

Adams, W.M., Sandbrook, C., 2013. Conservation, evidence and policy. Oryx 47 (3), 329–335.

Arksey, H., O'Malley, L., 2005. Scoping studies: towards a methodological framework. Int. J. Soc. Res. Methodol. 8 (1), 19–32.

Armitage, D.R., Plummer, R., Berkes, F., Arthur, R.I., Charles, A.T., Davidson-Hunt, I.J., Diduck, A.P., Doubleday, N.C., Johnson, D.S., Marschke, M., McConney, P., Pinkerton, E.W., Wollenberg, E.K., 2009. Adaptive co-management for social-ecological complexity. Front. Ecol. Environ. 7 (2), 95–102.

August, T., Harvey, M., Lightfoot, P., Kilbey, D., Papadopoulos, T., Jepson, P., 2015. Emerging technologies for biological recording. Biol. J. Linn. Soc. 115, 731–749.

Ballard, H.L., Robinson, L.D., Young, A.N., Pauly, G.P., Higgins, L.M., Johnson, R.F., Tweddle, J.C., 2017. Contributions to conservation outcomes by natural history museum-led citizen science: examining evidence and next steps. Biol. Conserv. 208, 87–97.

Ballard, H.L., Phillips, T.B., Robinson, L., 2018. Conservation outcomes of citizen science. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 254–268. https://doi.org/10.14324/111.9781787352339.

Barbour, W., Schlesinger, C., 2012. Who's the boss? Post-colonialism, ecological research and conservation management on Australian indigenous lands. Ecological Management & Restoration 13 (1), 36–41.

Baruch, A., May, A., Yu, D., 2016. The motivations, enablers and barriers for voluntary participation in an online crowdsourcing platform. Comput. Hum. Behav. 64, 923–931.

Berkes, F., Berkes, M. Kislalioglu, Fast, H., 2007. Collaborative integrated management in Canada's north: the role of local and traditional knowledge as community-based monitoring. Coast. Manag. 35, 143–162.

Berrang-Ford, L., Pearce, T., Ford, J.D., 2015. Systematic review approaches for climate change adaptation research. Reg. Environ. Chang. 15, 755–769.

Blaney, R.J.P., Jones, G.D., Philippe, A.C.V., Pocock, M.J.O., 2016. Citizen science and environmental monitoring: towards a methodology for evaluating opportunities, costs and benefits. In: Final Report on Behalf of UKEOF. WRc, Fera Science, Centre for Ecology & Hydrology.

Bonney, R., Shirk, J.L., Phillips, T.B., Wiggins, A., Ballard, H.L., Miller-Rushing, A.J., Parrish, J.K., 2014. Next steps for 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 Underst. Sci. 25 (1), 2–16.

Brammer, J.R., Brunet, N.D., Burton, A.C., Cuerrier, A., Danielsen, F., Dewan, K., Herrmann, T.M., Jackson, M.V., Kennett, R., Larocque, G., Mulrennan, M., Pratihast, A.K., Saint-Arnaud, M., Scott, C., Humphries, M.M., 2016. The role of digital data entry in participatory environmental monitoring. Conserv. Biol. 30 (6), 1277–1287.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101.

Brovelli, M.A., Minghini, M., Zamboni, G., 2016. Public participation in GIS via mobile applications. ISPRS J. Photogramm. Remote Sens. 114, 306–315.

Cairney, P., Oliver, K., 2018. How should academics engage in policy making to achieve impact? Political Studies Review 1–17 online first.
Callaghan, C.T., Lyons, M.B., Martin, J.M., Major, R.E., Kingsford, R.T., 2017. Assessing the reliability of avian biodiversity measures of urban greenspaces using eBird citizen science data. Avian Conservation and Ecology 12 (2), 12. https://doi.org/10.5751/ACE-01104-120212.
Catalano, A.S., Redford, K.H., Margolius, R., Knight, A.T., 2018. Black swans, cognition and the power of learning from failure. Conserv. Biol. 32 (3), 584–596.
Chapron, G., 2015. Wildlife in the cloud: a new approach for engaging stakeholders in wildlife management. Ambio 44 (Suppl. 4), S550–S556.
Charriere, M.K.M., Bogaard, T.A., 2016. Smartphone applications for communicating avalanche risk information – a study on how they are developed and evaluated by their providers. Nat. Hazards Earth Syst. Sci. 16, 1175–1188.
Connors, J.P., Lei, S., Kelly, M., 2012. Citizen science in the age of neogeography: utilizing volunteered geographic information for environmental monitoring. Ann. Assoc. Am. Geogr. 102 (6), 1267–1289.
Conrad, C., 2006. Towards meaningful community-based ecological monitoring in Nova Scotia: where are we versus where we would like to be. Environments 34, 25e36.
Conrad, C.C., Hilchey, K.G., 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ. Monit. Assess. 176, 273–291.
Cooper, C.B., Lewenstein, B.V., 2016. Two meanings of citizen science. In: Cavalier, D. (Ed.), The Rightful Place of Science: Citizen Science. Arizona State University Press, Tempe, AZ, pp. 51–62.
Cooper, C.B., Larson, L.R., Holland, K.K., Gibson, R.A., Farnham, D.J., Hsueh, D.Y., Culligan, P.J., McGillis, W.R., 2017. Contrasting the views and actions of data collectors and data consumers in a volunteer water quality monitoring project: implications for project design and management. Citizen Science: Theory and Practice 2 (1), 1–14.
Cornell, J., 2017. Naturewatch: lessons from the field of app development. Published online 21 June 2017. https://www.wildlabs.net/resources/case-studies/naturewatch-lessons-field-app-development, Accessed date: 14 January 2019.
Covidence, 2018. Covidence Systematic Review Software. Veritas Health Innovation, Melbourne, Australia. www.covidence.org.
Cvitanovic, C., Hobday, A.J., van Kerkhoff, L., Wilson, S.K., Dobbs, K., Marshall, N.A., 2015. Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: a review of knowledge and research needs. Ocean & Coastal Management 112, 25–35.
Danielsen, F., Burgess, N.D., Balmford, A., Donald, P.F., Funder, M., Jones, K.P.G., Alviola, P., Balete, D.S., Blomley, T., Brashares, J., Child, B., Enghoff, M., Fjeldsa, J., Holt, S., Hubertz, H., Jensen, A.E., Jensen, P.M., Massao, J., Mendoza, M.M., Ngaga, Y., Poulsen, M.K., Rudea, R., Sam, M., Skielboe, T., Stuart-Hill, G., Topp-Jorgensen, E., Yonten, D., 2009. Local participation in natural resource monitoring: a characterization of approaches. Conserv. Biol. 23 (1), 31–42.
Devisch, O., Veestraeten, D., 2013. From sharing to experimenting: how mobile technologies are helping ordinary citizens regain their positions as scientists. J. Urban Technol. 20 (2), 63–76.
Dewan, S., Riggins, F.J., 2005. The digital divide: current and future research directions. J. Assoc. Inf. Syst. 6 (12), 298–337.
Dorward, L.J., Mittermeier, J.C., Sandbrook, C., Spooner, F., 2017. Pokemon Go: benefits, costs, and lessons for the conservation movement. Conserv. Lett. 10 (1), 160–165.
Edwards, R., Kirn, S., Hillman, T., Kloetzer, L., Mathieson, K., McDonnell, D., Phillips, T., 2018. Learning and developing science capital through citizen science. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 381–390. https://doi.org/10.14324/111.9781787352339.
Eitzel, M.V., Cappadonna, J.L., Santos-Lang, C., Duerr, R.E., Virapongse, A., West, S.E., Kyba, C.C.M., Bowser, A., Cooper, C.B., Sforzi, A., Metcalfe, A.N., Harris, E.S., Thiel, M., Haklay, M., Ponciano, L., Roche, J., Ceccaroni, L., Shilling, F.M., Dörler, D., Heigl, F., Kiessling, T., Davis, B.Y., Jiang, Q., 2017. Citizen science terminology matters: exploring key terms. Citizen Science: Theory and Practice 2 (1), 1–20.
Ferster, C.J., Coops, N.C., 2013. A review of earth observation using mobile communication devices. Comput. Geosci. 51, 339–349.
Graham, M., 2011. Time machines and virtual portals: the spatialities of the digital divide. Prog. Dev. Stud. 11 (3), 211–227.
Groom, Q., Weatherdon, L., Geijzendorffer, I.R., 2017. Is citizen science an open science in the case of biodiversity observations? J. Appl. Ecol. 54, 612–617.
Haklay, M., 2013. Citizen science and volunteered geographic information –overview and typology of participation. In: Sui, Elwood, Goodchild (Eds.), Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice. Springer, Berlin, pp. 105–122. https://doi.org/10.1007/978-94-007-4587-2_7.
Heaney, C.D., Wilson, S.M., Wilson, O.R., 2007. The West End Revitalization Association's community-owned and -managed research model: development, implementation, and action. Prog. Community Health Partnersh. 1 (4), 339–349.
Hochachka, W.M., Fink, D., Hutchinson, R.A., Sheldon, D., Wong, W., Kelling, S., 2012. Data-intensive science applied to broad-scale citizen science. Trends in Ecology and Evolution 27 (2), 130–137.
Holling, C.S., Meffe, G.K., 1996. Command and control and the pathology of natural resource management. Conserv. Biol. 10, 328–337.
Jepson, P., Ladle, R.J., 2015. Nature apps: waiting for the revolution. Ambio 44, 827–832.
Kellert, S.R., Mehta, J.N., Ebbin, S.A., Lichtenfeld, L.L., 2000. Community natural resource management: promise, rhetoric, and reality. Soc. Nat. Resour. 13, 705–715.
Kohler, F., Brondizio, E.S., 2017. Considering the needs of indigenous and local populations in conservation programs. Conserv. Biol. 31 (2), 245–251.
Kouril, D., Furgal, C., Whillans, T., 2016. Trends and key elements in community-based monitoring: a systematic review of the literature with an emphasis on Arctic and Subarctic regions. Environ. Rev. 24 (2), 151–163.
Leao, S., Izadpahani, P., 2016. Factors motivating citizen engagement in mobile sensing: insights from a survey of non-participants. J. Urban Technol. 23 (4), 85–103.
Levac, D., Colquhoun, H., O'Brien, K.K., 2010. Scoping studies: advancing the methodology. Implement. Sci. 5, 69.
Luna, S., Gold, M., Albert, A., Ceccaroni, L., Claramunt, B., Danylo, O., Haklay, M., Kottmann, R., Kyba, C., Piera, J., Radicchi, A., Schade, S., Sturm, U., 2018. Developing mobile applications for environmental and biodiversity citizen science: considerations and recommendations. In: Joly, Vrochidis, B., Karatzas, Karppinen, Bonnet (Eds.), Multimedia Tools and Applications for Environmental & Biodiversity Informatics. Springer, Cham, pp. 9–30.
Mazumdar, S., Ceccaroni, L., Piera, J., Holker, F., Berre, A.J., Arlingaus, R., Bowser, A., 2018. Citizen science technologies and new opportunities for participation. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 303–320. https://doi.org/10.14324/111.9781787352339.
McKinley, D.C., Miller-Rushing, A.J., Ballard, H.L., Bonney, R., Brown, H., Cook-Patton, S.C., Evans, D.M., French, R.A., Parrish, J., Phillips, T.B., Ryan, S.F., Shanley, L.A., Shirk, J.L., Stepenuck, K.F., Weltzin, J.F., Wiggins, A., Boyle, O.D., Briggs, R.D., Chapin III, S.F., Hewitt, D.A., Preuss, P.W., Soukup, M.A., 2017. Citizen science can improve conservation science, natural resource management, and environmental protection. Biol. Conserv. 208, 15–28.
Mendeley, 2018. Mendeley Reference Manager. Mendeley Limited. https://www.mendeley.com.
Nascimento, S., Iglesias, J.M.R., Owen, R., Schade, S., Shanley, L., 2018. Citizen science for policy formulation and implementation. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 219–240. https://doi.org/10.14324/111.9781787352339.
National Academies of Sciences, Engineering, and Medicine (NASEM), 2018. Learning Through Citizen Science: Enhancing Opportunities by Design. The National Academies Press, Washington, DC. https://doi.org/10.17226/25183.
Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. Front. Ecol. Environ. 10 (6), 298–304.
NVivo, 2018. NVivo Qualitative Data Analysis Software. QSR International Pty Ltd (Version 12).
Owen, R.P., Parker, A.J., 2018. Citizen science in environmental protection agencies. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 284–300. https://doi.org/10.14324/111.9781787352339.
Peltola, T., Arpin, I., 2018. Science for everybody? Bridging the socio-economic gap in urban biodiversity monitoring. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 369–380. https://doi.org/10.14324/111.9781787352339.
Pimm, S.L., Alibhai, S., Bergl, R., Dehgan, A., Giri, C., Jewell, Z., Joppa, L., Kays, R., Loarie, S., 2015. Emerging technologies to conserve biodiversity. Trends Ecol. Evol. 30 (11), 685–696.
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 (4), e0172579. https://doi.org/10.1371/journal.pone.0172579.
Preece, J., 2016. Citizen science: new research challenges for human-computer interaction. International Journal of Human-Computer Interaction 32 (8), 585–612.
Raymond, C.M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., Evely, A.C., 2010. Integrating local and scientific knowledge for environmental management. J. Environ. Manag. 91, 1766–1777.
Sauermann, H., Franzoni, C., 2015. Crowd science user contribution patterns and their implications. PNAS 112 (3), 679–684.
Sharma, N., Greaves, S., Siddharthan, A., Anderson, H.B., Robinson, A., Colucci-Gray, L., Wibowo, A.T., Bostock, H., Salisbury, A., Roberts, S., Slawson, D., van der Wal, R., 2019. From citizen science to citizen action: analysing the potential for a digital platform to cultivate attachments to nature. J. Sci. Commun. 18 (1), A07.
Shirk, J.L., Ballard, H.L., Wilderman, C.C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B.V., Krasny, M.E., Bonney, R., 2012. Public participation in scientific research: a framework for deliberate design. Ecol. Soc. 17 (2), 29.
Silver, J.J., Hawkins, R., 2017. “I'm not trying to save fish, I'm trying to save dinner”: media, celebrity and sustainable seafood as a solution to environmental limits. Geoforum 84, 218–227.
Skarlatidou, A., Hamilton, A., Vitos, M., Haklay, M., 2019. What do volunteers want from citizen science technologies? A systematic literature review and best practice guidelines. J. Sci. Commun. 18 (1), A02.
Smith, L.T., 1999. Decolonizing Methodologies: Research and Indigenous Peoples. Zed Books/St Martin's Press, New York, USA.
Spiers, H., Swanson, A., Fortson, L., Simmons, B.D., Trouille, L., Blockhan, S., Lintott, C., 2019. Everyone counts? Design considerations in online citizen science. J. Sci. Commun. 18 (1), A04.
Starr, J., Schweik, C.M., Bush, N., Fletcher, L., Finn, J., Fish, J., Bargeron, C.T., 2014. Lights, camera… citizen science: assessing the effectiveness of smartphone-based video training in invasive plant identification. PLoS One 9 (11), e111433.
Stephanson, S.I., Mascia, M.B., 2014. Putting people on the map through an approach that integrates social data in conservation planning. Conserv. Biol. 28 (5), 1236–1248.
Sturm, U., Schade, S., Ceccaroni, L., Gold, M., Kyba, C.C.M., Claramunt, B., Haklay, M., Kasperowski, D., Albert, A., Piera, J., Brier, J., Kullenberg, C., Luna, S., 2017. Defining principles for mobile apps and platforms development in citizen science. Research Ideas and Outcomes 3, e21283.

Sui, D., Goodchild, M.F., Elwood, S., 2012. Volunteered geographic information, the exaflood, and the growing digital divide. In: Sui, Elwood, Goodchild (Eds.), Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice. Springer, Netherlands, pp. 1–12. https://doi.org/10.1007/978-94-007-4587-2_1.
Sullivan, J.J., Molles, L.E., 2016. Biodiversity monitoring by community-based restoration groups in New Zealand. Ecological Management & Restoration 17 (3), 210–217.
Sullivan, B.L., Phillips, T., Dayer, A.A., Wood, C.L., Farnsworth, A., Iliff, M.J., Davies, I.J., Wiggins, A., Fink, D., Hochachka, W.M., Rodewald, A.D., Rosenverg, K.V., Bonney, R., Kelling, S., 2017. Using open access observational data for conservation action: a case study for birds. Biol. Conserv. 208, 5–14.
Sutherland, W.J., Pullin, A.S., Dolman, P.M., Knight, T.M., 2004. The need for evidence-based conservation. Trends in Ecology and Evolution 19 (6), 305–308.
Teacher, A.G.F., Griffiths, D.J., Hodgson, D.J., Inger, R., 2013. Smartphones in ecology and evolution: a guide for the apprehensive. Ecology and Evolution 3 (16), 5268–5278.
Toomey, A.H., Knight, A.T., Barlow, J., 2017. Navigating the space between research and implementation in conservation. Conserv. Lett. 10 (5), 619–625.
Verma, A., van der Wal, R., Fischer, A., 2016. Imagining wildlife: new technologies and animal censuses, maps and museums. Geoforum 75, 75–86.
Wald, D.M., Longo, J., Dobell, A.R., 2016. Design principles for engaging and retaining virtual citizen scientists. Conserv. Biol. 30 (3), 562–570.
Weiss, J.W., Gulati, G.J., Yates, D.J., Yates, L.E., 2015. Mobile broadband affordability and the global digital divide, an information ethics perspective. In: 48th Hawaii International Conference on System Sciences, https://doi.org/10.1109/HICSS.2015.261. Koloa, Kauai, HI.
Weiss, J.W., Yates, D.J., Gulati, J.G., 2016. Affordable broadband: bridging the global digital divide, a social justice approach. In: Academy of Management Annual Meeting Proceedings. Anaheim, CA.
Wiggins, A., 2012. Crowdsourcing Scientific Work: A Comparative Study of Technologies, Processes, and Outcomes in Citizen Science. School of Information Studies. PhD Dissertation. https://surface.syr.edu/it_etd/72.
Wiggins, A., 2013. Free as in puppies: compensating for ICT constraints in citizen science. In: Proceedings of the ACM International Conference on Computer-supported Cooperative Work and Social Computing, (San Antonio, TX).
Williams, J., Chapman, C., Leibovici, D.G., Lois, G., Matheus, A., Oggioni, A., Schade, S., See, L., van Genuchten, P.P.L., 2018. Maximizing the impact and reuse of citizen science data. In: Hecker, Haklay, Bowser, Makuch, Vogel, Bonn (Eds.), Citizen Science: Innovation in Open Science, Society and Policy. UCL Press, London, UK, pp. 321–336. https://doi.org/10.14324/111.9781787352339.
Wilson, N.J., Mutter, E., Inkster, J., Satterfield, T., 2018. Community-based monitoring as the practice of indigenous governance: a case study of indigenous-led water quality monitoring in the Yukon River Basin. J. Environ. Manag. 210, 290–298.