Appendix A

Table showing the categories of benefits, outcomes and impacts arising from the literature review and a brief description of them. Some categories appear in multiple pathways but in this table are only included on their first mention.

Pathway and stage	Category in Figures 2-4	Original category	Description	Example reference and quote from abstract
Short term data outcomes: Pathway 1 More data	More data	More data	Generate/process more data than would be possible than scientists working on their own	"Our study…provides a model for using citizen science data for biodiversity research in a large developing country with few professional field biologists." (Abolafaya et al. 2013)
	Less time and money used	Time saving	Faster data collection / processing	"monitoring roads for flattened fauna is a time consuming effort and roadkill monitoring projects conducted up till now have been relatively small scale both in terms of time and space…We demonstrate that citizen science projects in combination with smartphones and other new technologies allow analysis at this level and extent, and simultaneously offer more complete data for safer transportation and mitigation of roadkill hotspots." (Vercayie and Herremans 2015)
		Money saving	Cheaper collection / processing of data than professional scientists	"The estimated project costs were almost US$ 23,000 if only researchers were involved in the effort, but the inclusion of volunteers in fieldwork and data analyses could help to bring the expenditure down by up to 23%." (Toh et al. 2017)
	Finer spatial resolution and greater spatial extent	Greater spatial extent of data	Data generated over a larger geographic area	"We classify the goals of citizen science in ecology and environment…we review the literature showing that these projects are most effective in tracking ecological trends over large swaths of space" (Adler, Green and Şekercioğlu 2020)
		Spatial density	Data at a finer	"The citizen-science approach provided unprecedented

		of data	spatial resolution	density of data from 1,700 localities.” (Aavik et al. 2020)
	Greater spatial diversity	Spatial diversity of data	Data across a variety of e.g. habitat/landscape types	“We collated location records of P. muralis presence in England, UK through data collected from field surveys and a citizen science campaign. We used these data as input for presence-background models to predict areas of climate suitability at a national-scale (5 km resolution), and fine-scale habitat suitability at the local scale (2 m resolution).” (Williams et al. 2021)
	Finer temporal resolution and greater temporal extent	Temporal resolution	Frequent data collection	“Managing to support coral reef resilience as the climate changes requires strategic and responsive actions that reduce anthropogenic stress. Managers can only target and tailor these actions if they regularly receive information on system condition and impact severity…acquiring condition and impact data with good spatial and temporal coverage requires using a large network of observers. Here, we describe the result of similar to 10 years of evolving and refining participatory monitoring programs used in the GBR that have rangers, tourism operators and members of the public as observers.” (Beeden et al. 2014)
		Temporal duration	Data collection over a long period of time	“We provide the first quantitative review of biodiversity-related citizen science to determine whether data collected by these projects can be, and are currently being, effectively used in biodiversity research. We find strong evidence of the potential of citizen science: within projects we sampled (n = 388), similar to 1.3 million volunteers participate, contributing up to $2.5 billion in-kind annually. These projects exceed most federally-funded studies in spatial and temporal extent” (Theobald et al. 2015)
	Rapid generation of data	Rapid data generation	Data generated quickly e.g. in response to a	“Natural hazard research and disaster management also benefit from CitSci since people can provide geodata and the relevant attributes using their mobile devices easily and

			disaster	rapidly during or after an event.” (Yalcin et al. 2020)
	Otherwise inaccessible data included	Inaccessible data	Data from places/situations scientists wouldn’t typically have access to	“Legal and policy initiatives to address the environmental dimensions of armed conflicts and their impact on people, ecosystems and sustainable development are highly dependent on the availability of environmental data from conflict-affected areas. Socio-political and security conditions in these areas often impede data collection, while traditional models of post-conflict environmental assessments are limited in scope. In response, an increasing range of actors is utilising remote sensing and open source data collection to identify and estimate health and ecological risks during and after conflicts. This paper considers the role of participatory citizen science methodologies in complementing both remote monitoring and post-conflict assessments. It examines existing models and mechanisms for environmental data collection and utilisation in conflict contexts, and the extent to which the core values and principles of citizen science are transferable. We find that 'civilian science' is feasible and could be well-suited to conflict conditions.” (Weir, McQuillan and Francis 2019)
	Data about marginalised or understudied people included	Diversity	Inclusion of a greater diversity of people in research	“Health interventions often do not reach blue-collar workers. Citizen science engages target groups in the design and execution of health interventions, but has not yet been applied in an occupational setting. This preliminary study determines barriers and facilitators and feasible elements for citizen science to improve the health of blue-collar workers.” (van den Berge et al. 2020)

Short term data outcomes: Pathway 2 Richer data	Datasets drawn from people's lived experiences	Lived experience	Deeper, richer more nuanced data accompanied by context.	"To date, all available studies designed to investigate the psychological effects of this unprecedented global crisis are based on cross-sectional surveys that do not capture emotional variations over time. Here, we present the data from CoVidAffect, a nationwide citizen science project aimed to provide longitudinal data of mood changes following the COVID-19 outbreak in the spanish territory." (Bailon et al. 2020)
	Datasets reveal public perceptions	Understand public perceptions	Projects aim to understand what people know or think about a topic	"The quality of public green spaces is mostly measured through expert assessments by planners, designers and developers. A disadvantage of this expert-determined approach is that it often does not consider the appraisals or perceptions of residents…The aim of this Australian pilot study on public green spaces for ageing well was to test an innovative citizen science approach to data collection using smart phones. "Senior" citizen scientists trialed the smart phone audit tool over a three-month period, recording and auditing public green spaces in their neighbourhoods." (Barrie et al. 2019)
	Local, traditional and indigenous knowledge included	Include local and traditional knowledge	Projects seek to capture local and indigenous knowledge	"We recommend for adoption and promotion of the CIEI perspective in areas where such approaches appear defensible for the assessment of catchment-wide practices in areas with robust indigenous knowledge to provide a broad-view of the ecological health of the aquatic ecosystem." (Aura et al. 2021)
Short term data outcomes: Pathway 3 Open data	Open data	Open access data	Data collected are openly available	"Citizen science programs are often promoted as being able to achieve multiple scientific (e.g. quality data and open sharing of data) and social goals (e.g. increased transparency and public trust)" (Anhalt-Depies et al. 2019)
Medium-term	New knowledge	New scientific	Data collected led to	"Whale sharks from Panaon Island were identified through

data outcomes	generated	knowledge	new (scientific) knowledge	photo-ID and citizen science at other sites in the Philippines, as well as a match to Taiwan, representing the first international match through photo-ID in South-east Asia with a minimum distance covered of 1600 km." (Araujo et al. 2017)
	Baseline / snapshot assessment performed	Snapshot assessment	To gain an understanding of an issue at a particular point in time	"Here, we report results from a global diver survey used to set baselines of shark populations" (Ward-Paige and Worm 2017)
	Long-term monitoring performed	Monitoring	Data used to track a particular issue over time	"we analyze spring arrival data for two long-distance migrants (Ruby-throated Hummingbird Archilochus colubris; and Purple Martin Progne subis) in eastern North America from 2001-2010 using Citizen Science data." (Arab, Courter and Zelt 2016)
	Indicator monitoring and target tracking	Indicator monitoring and target tracking	Tracking progress towards goals/targets	"Biodiversity indicators are essential for monitoring the impacts of pressures on the state of nature, determining the effectiveness of policy responses, and tracking progress towards biodiversity targets and sustainable development goals. Indicators based on trends in the abundance of birds are widely used for these purposes in Europe and have been identified as priorities for development elsewhere. To facilitate this we established bird population monitoring schemes in three African countries, based on citizen science approaches used in Europe, aiming to monitor population trends in common and widespread species." (Wotton et al. 2020)
	Impacts of events and interventions assessed	Assessing events	Data are used to assess the impact of events	Legal and policy initiatives to address the environmental dimensions of armed conflicts and their impact on people, ecosystems and sustainable development are highly dependent on the availability of environmental data from conflict-affected areas…We find that 'civilian science' is feasible and could be well-suited to conflict conditions…addressing gaps in data collection" (Weir,

				McQuillan and Francis 2019)
		Assessing interventions	Data are used to assess the effectiveness of conservation interventions	“We modeled detection and occupancy of species at sites within 42 conservation project wetlands compared to sites within 52 similar nearby unmanaged wetlands throughout southern Ontario, Canada, and small portions of the adjacent U.S., using citizen science data collected by Bird Studies Canada's Great Lakes Marsh Monitoring Program” (Tozer, Steele and Gloutney 2018)
	Surveillance conducted	Surveillance	To provide an early warning system	“The recent expansion of the hazardous fish Lagocephalus sceleratus in the Straits of Sicily, the subsequent actions adopted to manage the risk and the feedback received from the public are herein presented, as an example of the interaction between experts and the public in promoting scientific citizenship through an ad hoc action.” (Andaloro et al. 2016)
	Datasets accessed and used by others	**Authors’ addition**		
Long-term data outcomes	New scientific questions, targets and avenues identified	New scientific questions	Project stimulated new hypotheses/questions/targets	“Citizen-science data about the morph type of Primula veris across Estonia obtained with the help of thousands of people demonstrates that in addition to plant population size, landscape context may affect plant reproductive traits, such as heterostyly. Larger population size of P. veris can help to buffer against random fluctuations in this trait. Increasing impact of human activities may have a negative impact on both small and large populations. The exact underlying mechanisms of the prevalence of one morph over the other, however, pose novel questions for further research.” (Aavik et al. 2020)
	(More	Inform decision-	Informs decision	“MedSens converts the data collected by trained volunteers

	representative) policy- and decision-making	making	making at range of scales and contexts e.g. land management decisions, community action plans, urban planning	into an effective monitoring tool for the Mediterranean subtidal rocky coastal habitats. MedSens can help conservationists and decision-makers identify the main pressures acting in these habitats, as required by the MSFD, supporting them in the implementation of appropriate marine biodiversity conservation measures and better communicate the results of their actions." (Turicchia et al. 2021a)
		Inform policy-making	Projects aim to inform policy making (at a range of scales)	"An emerging and promising approach to achieving access to water and sanitation for all leverages citizen science to collect valuable data on water quantity and quality, which can assist policy-makers and water utility managers in sustainably managing water resources." (Xing et al. 2019)
	More societally relevant and trusted science	Democratisation of science	More societally relevant science conducted	"Citizen science (CS) aims primarily to create a new scientific culture able to improve upon the triple interaction between science, society, and policy in the dual pursuit of more democratic research and decision-making informed by sound evidence." (Bautista-Puig et al. 2019)
Short term participant outcomes: Pathway 4 Knowledge and skills	Participants gain knowledge	Participants gain knowledge	Participants learn something or gain knowledge	"To foster environmental and conservation goals, citizen science can (i) generate new knowledge, (ii) enhance awareness raising and facilitate in-depth learning as well as (iii) enable civic participation." (Turrini et al. 2018)
	Scientists raise awareness of issues	Awareness raising	Projects raise awareness of issues amongst participants	"Our project was also successful in raising public awareness about the importance of plant breeding and in communicating key messages on the manifold benefits of legumes for a sustainable agriculture to a broader public. Thus, citizen science appears as a promising avenue to demonstrate the value of breeding and science to the general public by including normal citizens in scientific research." (Wurschum et al. 2019)

	Participants gain understanding of personal circumstances	Personal understanding	Participants get data/information about themselves or their own situation	“Individual-level report-back of environmental data is a powerful tool for individuals to understand and act on their personal exposure to heat.” (Thompson, Sugg and Runkle 2018)
	Participants gain skills and qualifications	Participants gain skills	Participants gain skills, e.g. practical, technical and communication skills	“Post-survey-based evaluation revealed that this project allowed university students to acquire diverse personal, social and scientific skills” (Antunes et al. 2021)
		Formal education	Citizen science used as part of formal education programmes e.g. in schools or universities	“This study evaluated the effectiveness of participation by elementary school students in educational activities and citizen science actions in enhancing their scientific knowledge and skills related to Ocean Literacy in the context of climate change.” (Boaventura et al. 2021)
Short term participant outcomes: Pathway 5 Science capital	Wider participation and engagement in science	Public engagement	Increase public engagement with science	“Several CS projects have generated interesting results in terms of scientific findings and public engagement.” (Bargnesi Lucrezi and Ferretti 2020)
		Widen participation	Increases the diversity of people engaged within science	“Through their unique combination of specimen collections, scientific and public education expertise, and wide audience reach and trust, natural history museums (NHMs) are obvious settings for bridging conservation science and education through citizen science.” (Ballard et al. 2017)
	Participants increase scientific skills	Scientific skills	Participants gain other scientific skills, including practical skills	“At a process level, participants learned laboratory techniques (sieving, gravity and reduced pressure filtrations and crystallization) and the handling of laboratory materials.” (Araujo, Morais and Paiva 2022)
	Participants increase science literacy	Scientific literacy	Participants can e.g. identify scientific questions, and make	“The exploratory research involved an intervention with two design studies of adult volunteer participants engaging in citizen-led inquiries, employing a mixed-methods approach.

			evidence-based conclusions	The findings indicated that, in both design studies, participants engaged in an inquiry process, and practised inquiry skills" (Aristeidou et al. 2020)
	Participants value and appreciate science	Science appreciation	Participants understand/appreciate science e.g. its relevance to their lives	"Mixed-methods assessment of citizen science within a college classroom demonstrates that public participation in scientific research can positively alter attitudes towards science." (Vitone et al. 2016)
	Participants increase science identity	Science identity	Participants develop a science identity (feel they are a scientist)	"This study evaluated the effects of a classroom-based citizen science project in which middle and high school students collected data about hummingbirds and their habitat use as part of a long-term study on declining hummingbird populations. We explored changes in science identity" (Williams et al. 2021)
Short term participant outcomes: Pathway 6 Empowerment	Participants are empowered	Participant empowerment	Participants are empowered (i.e. have the strength and power to control their life)	"We present the Our Voice framework, developed by researchers at Stanford University, as a promising strategy for engaging and empowering older people as citizen scientists, as a framework to apply to gerontological nursing and improving community health." (Tucker et al. 2018)
	Participants are motivated	Motivation	Participants are motivated through participation	"The project provided a focus to motivate and connect teachers, academic staff, and school students during a difficult circumstance." (Van Haeften et al. 2021)
	Participants gain self determination	Self determination	Participation leads to greater self determination and control (beyond the research process)	"These changes focused on: parks/playgrounds, footpaths, and traffic related safety/parking. Project results suggest that the Our Voice approach can be an effective strategy for the global goals of advancing rights and increasing self-determination among older adults." (Tuckett et al. 2018b)
Short term participant	Participants gain or strengthen	Nature connection	Participants connect with nature	"By encouraging participation of a wide range of people, such activities could provide an opportunity for people to become

outcomes: Pathway 7 Meaning and connection	connection with nature			more connected with nature." (Woolley et al. 2021)
	Participants gain or strengthen a sense of place	Sense of place	Participants connect with/understand a particular place	"We found that place-based citizen science can strengthen attachment to the personal, social, and environmental dimensions of place, and additionally has the potential to enhance both individual and collective social-ecological meanings of place through active processes of place - making." (Toomey et al. 2020)
	Participants gain a deeper meaning from hobbies	Deeper meaning to hobbies	Give purpose to people's existing hobbies / interests	"We find limited but growing evidence that citizen science projects…provide deeper meaning to participants' hobbies." (Bonney et al. 2016)
	Communities are formed or strengthened	Community building	Relationships between participants are built	"Feedback from the participants demonstrated reflexivity about social learning and a renewed sense of community built around generating reliable and useful data." (Appels et al. 2017)
Medium term participant outcomes	Participants pursue new career opportunities	**Authors' addition**		
	Participants change their values and perspectives	Change perceptions	Projects aim to alter participants' (and other citizens') attitudes or perceptions	"We discuss two citizen science projects in the New York metropolitan area the Great Pollinator Project and the Earthwatch Coyote Project as illustrations of the impact of citizen science on attitudes and behaviors as perceived by participants" (Toomey and Domroese 2013)
	Participants pursue science careers	Science careers	Encourage/support people into science careers	"Over two years and three projects, this crowd has produced articles at top-tier Computer Science venues, and participants have gone on to leading graduate programs." (Vaish et al. 2017)

	Participants change behaviour	Behaviour change	Projects aim to bring about behaviour change in participants	“Using citizen science and mass media appeared to be associated with changes in night-time smartphone behavior. Public health projects may benefit from combining citizen science with other interventional approaches.” (Andersen et al. 2021)
	Participants have trust and buy in to science	Trust	Trust in science and decision-making	“Citizen science programs are often promoted as being able to achieve multiple scientific (e.g. quality data and open sharing of data) and social goals (e.g. increased transparency and public trust)” (Anhalt-Depies et al. 2019)
	Participants take direct action	Participants decision making	Participants gain understanding to make decisions or take action	“A systematic review was conducted, seeking to examine how citizens' participation in environmental CS initiatives contributes to the EEC, as a venue through which citizens can undertake actions in different scales (local, national, global)” (Adamou et al. 2021)
	Participants become advocates	Advocacy	Participants become advocates i.e. aim to influence decision-making	“We also provide evidence for the efficacy of utilizing citizen science in research, as the broader impact of this work is to empower local communities to advocate for improving their own water quality” (Babich et al. 2021)
	Participants show wider civic engagement	Civic engagement	Increased engagement of the public in issues of public concern	“to foster environmental and conservation goals, citizen science can (i) generate new knowledge, (ii) enhance awareness raising and facilitate in-depth learning as well as (iii) enable civic participation.” (Turrini et al. 2018)
	Participants increase citizenship and stewardship	Environmental citizenship	Enhancing environmental values, support, ownership and action	“Public participation in scientific research (hereby referred to as citizen science) is often touted as a way to help people get to know, connect with, and care for an ecological place.” (Toomey et al. 2020)
	Participants increase social	Social capital	Project develops participants’	“Citizen science projects are increasingly recognised as catalyst for triggering behaviour change and building social

	capital		networks, norms and social trust	capital around environmental issues." (Van Brussel and Huyse 2019)
Long term participant outcomes	Participants experience upward mobility	Upward mobility	Participants have access to e.g. better jobs as a result of participating	"Providing open access to research experiences would enable global upward mobility" (Vaish et al. 2017)
	Greater diversity in scientific workforce	Diversity in science careers	Encourage/support a greater diversity of people into science careers	"Research experiences today are limited to a privileged few at select universities. Providing open access to research experiences would enable global upward mobility and increased diversity in the scientific workforce." (Vaish et al. 2017)
	Communities are more resilient	Community building	Communities become stronger and more resilient	"The participatory action research approach, combined with digital citizen science, advances the cocreation of knowledge and multidisciplinary collaboration in the digital age. Given the urgency of climate change, leveraging technology provides communities with tools to respond to existing and emerging crises in a timely manner, as well as scientific evidence regarding the urgency of current health and environmental issues." (Bhawra et al. 2021)
	Participants have improved health and wellbeing	Health and wellbeing	Health and wellbeing benefits of participating in citizen science	"We contend that Citizen Science programs that facilitate exposure to NEs in urban areas may represent an important public health policy advance." (Williams et al. 2022)
	Rights of participants enhanced	Advancing rights	Projects lead to the advancing of the human rights of participants	"Project results suggest that the Our Voice approach can be an effective strategy for the global goals of advancing rights and increasing self-determination among older adults." (Tuckett et al. 2018b)
		Environmental human rights	Enhance the environmental	"In addition to addressing gaps in data collection, it may also empower communities affected by environmental

			human rights of participants	degradation, enhance their environmental human rights" (Weir, McQuillan and Francis 2019)
Short term collaboration outcomes: Pathway 8 Scientist-public collaborations	Co-production and generation of results	Shared knowledge	New knowledge is co-produced	"The two-way exchange of information between managers and participants increases the capacity to manage reefs adaptively" (Beeden et al. 2014)
	Participants gain autonomy	Participant autonomy	Participants have a sense of control in the research process	"This engagement gives volunteers the opportunity to feel like partners in the research and retain a reassuring sense of control over their participation." (Yu and Juengst 2020)
	Scientist-public relationships built	Scientist-public relationship	Building relationship between scientists / researchers and the public	"With appropriate and persistent institutional support and investment, citizen science can therefore have a lasting impact on how agricultural science engages with farming communities and wider society" (van de Gevel et al. 2020)
Short term collaboration outcomes: Pathway 9 wider collaborations	Partnerships and understanding built between stakeholders	Partnership building	Build partnerships / cooperation between organisations	"Citizen science can be used as an approach in Urban Living Labs, whereby public and private stakeholders are involved in innovation and data collection processes together with citizens." (Veeckman and Temmerman 2021)
	Trust and accountability built	Accountability	Hold e.g. decision-makers to account by being involved in data collection	"Made possible in part by new measurement techniques, including emerging sensor technologies, rapid impact evaluation, citizen science, and performance-based contracting, such systems have the potential to propel the development of solutions that can work over the long-term, allowing the benefits of environmental health improvements to be sustained in settings where they are most critical by improving trust and mutual accountability among stakeholders" (Thomas and Brown 2021)

	Public inclusion in decision-making	Public inclusion in decision-making	Include data/perspectives from public, including marginalised communities, in decision-making	“Concerns regarding the impacts of climate change on marginalised communities in the Global South have led to calls for affected communities to be more active as agents in the process of planning for climate change. While the value of involving communities in risk management is increasingly accepted, the development of appropriate tools to support community engagement in flood risk management projects remains nascent. Using the Revitalising Informal Settlements and their Environments Program as a case study, the article interrogates the potential of citizen science to include disadvantaged urban communities in project-level flood risk reduction planning processes. This project collected more than 5,000 photos taken by 26 community members living in 13 informal settlements in Fiji and Indonesia between 2018 and 2020. The case study documents the method used as well as the results achieved within this two-year project. It discusses the method developed and implemented, outlines the main results, and provides lessons learned for others embarking on citizen science environmental-monitoring projects. The case study indicates that the engagement model and the technology used were key to the success of the flood-monitoring project. The experiences with the practice of monitoring floods in collaboration with communities in Fiji and Indonesia provide insights into how similar projects could advance more participatory risk management practices. The article identifies how this kind of approach can collect valuable flood data while also promoting opportunities for local communities to be heard in the arena of risk reduction and climate change adaptation.” (Wolff et al. 2021)
	Space made for creativity	Creativity	Bringing diverse groups together increases creativity	“Specifically, we show how citizen science can reconfigure cost-motivation-accountability combinations using digital tools, open up a larger conceptual space of experimentation”

				(van de Gevel, van Etten and Deterding 2020)
	New interdisciplinary collaborations made	Interdisciplinary collaborations	Brings together scientists across disciplines	“We found that citizen science opens up four opportunities for creatively reshaping research: (i) new possibilities for interdisciplinary collaboration” (van de Gevel, van Etten and Deterding 2020)
	Capacity built and infrastructure developed	Capacity building and infrastructure development	Projects build capacity of partner organisations	“This robust community engagement in the project resulted in increased awareness, knowledge, capacity, infrastructure, and influence for the community partner organization and among community participants.” (Wong et al. 2020)
Medium-term collaboration outcomes	Scientists understand public priorities	**Authors’ addition**		
	Stakeholders have buy in to results	**Authors’ addition**		
	Public have buy in to results	Public buy in to results	Increased acceptability of decisions amongst participants and wider public	“By directly involving stakeholders, this approach increases public awareness and the acceptability of management decisions, enabling more participatory conservation tactics.” (Turicchia et al. 2021a)
Long-term collaboration outcomes	Innovative solutions to challenges identified	Innovation	Projects provide the space/infrastructure for innovation	“VHNs could integrate or expand the traditional pharmaceutical clinical trials; in such case, innovation will not be managed only internally by a company, but will be opened to patients' direct contribution.” (Trequattrini et al. 2015)