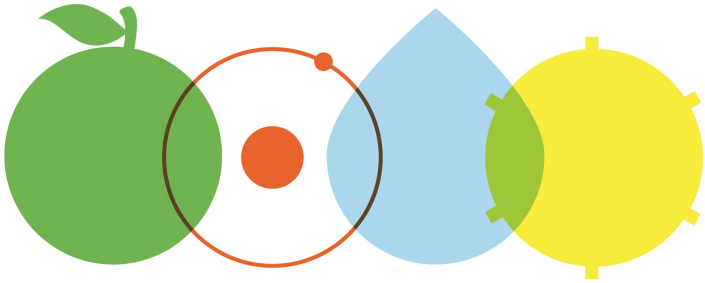

THE NEXUS NETWORK

new connections in food, energy, water and the environment

An ESRC investment

Exploring the nexus through citizen science

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About the Nexus Network think piece series

Funded by the ESRC, the Nexus Network is a collaboration between the University of Sussex, the STEPs Centre, the University of East Anglia, and the Cambridge Institute for Sustainability Leadership. The Nexus Network brings together researchers, policy makers, business leaders and civil society to develop collaborative projects and improve decision making on food, energy, water and the environment. In 2014, the Nexus Network commissioned a series of think pieces with the remit of scoping and defining nexus approaches, and stimulating debate across the linked domains of food, energy, water and the environment.

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Executive Summary

As global population increases, the connections between food, water, energy and the environment at global and regional scales become ever more important. The complexity and inter-connectedness of these relationships challenge policymakers, scientists, businesses and citizens to find acceptable ways forward, but there are no easy solutions. This is the 'nexus'. Citizen science can provide a powerful mechanism to help tackle these environmental and social challenges. In this thinkpiece we draw on the experiences of citizen science practitioners, particularly from the environmental sector.

Citizens are the guardians of their local environment and, arguably, often know the places where they live better than regulators, policymakers and industry. Local citizens will usually be the first to notice changes in their immediate environment, whether instant changes (such as a pollution spill) or gradual (such as species decline). Citizen science can generate and broaden out the kinds of data that are considered in the investigation of environmental issues. Benefits of participating in citizen science include raised awareness, increased education, greater involvement, more participatory democracy, and increased ownership of solutions. Participation may also bring wider social, health and wellbeing benefits. Professional scientists in turn benefit from the data submitted by volunteers, the value of which can be estimated at many millions of pounds per year.

Some of the generic challenges to successful citizen science will be heightened in the context of understanding and dealing with nexus issues. These include extending citizen science (which is normally conducted at local level) to regional and global scales, optimising the collection of data through better coordination between practitioners, empowering citizens and businesses to take more control of the conception and design of citizen science activities, and understanding the motivations, attitudes and practices of all participants.

Citizens are the sleeping giant on whose shoulders scientists must stand. This giant must be awoken and empowered to work with policymakers and businesses – and to hold them to account.

1. Introducing 'citizen science'

Citizen Science has been used in the scientific community since the mid-1990s but what do we mean by 'citizen science'? The term entered the Oxford English Dictionary for the first time in 2014, and describes it as "scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions"[1]. There are many alternative definitions, but consistent across them all is the involvement of people who are not professional scientists in scientific research and monitoring, often - but not always - in collaboration with professional scientists.

The level of citizen engagement varies between projects. Most commonly, projects are designed by professional scientists who then engage volunteers to (i) contribute data (for example the OPAL Air Survey[2] which asks participants to identify and record the presence of lichens as bioindicators of air quality), or (ii) carry out analysis of existing data (such as WhaleFM[3], which asks participants to classify recordings of whale calls to help scientists better understand how they communicate). Many projects are examples of crowdsourcing, where contributions from citizens are solicited en masse, often supported by online communication. Some approaches to citizen science engage citizens in multiple stages of a research project (for example, problem definition or activity design), in so-called 'collaborative' and 'co-created' projects.

While professional scientists are often involved in citizen science activities, this is not always the case. Projects may be specifically constructed to respond to local environmental issues that citizens perceive local authorities are not managing adequately[4]. A report on environmental citizen science for the European Commission[5] cites the example of the Achuar people of Peru who had for decades opposed oil companies drilling and disposing of wastewater on their land. With the support of the NGO Amazon Watch, the Achuar learnt how to use cameras and GPS technology to document the damage – evidence they used to bring a successful legal case against an oil company and to petition governments locally and abroad, resulting in another energy company ceasing activities in the area. Thus citizen science can support environmental justice for citizens (see I.4(c)).

Recommendation 1	Nexus scientists should take a broad definition of citizen science and consider a wide range of approaches and applications when assessing how it might contribute to nexus issues.

1.1 A (very) brief history of citizen science

Although the term "citizen science" is relatively recent, the concept is not new. During the nineteenth century, most scientists were amateurs and adventurers. Charles Darwin made his observations on the natural world during his voyage aboard *HMS Beagle* in the 1830s not in the capacity as professional scientist but as companion to the captain[6]. A common feature of these early volunteer scientists, who made valuable contributions to archaeology, astronomy, meteorology and natural history, was that they were largely unpaid for their efforts and tended to have independent sources of wealth.

Mass public participation in scientific data collection also has a long history. Silvertown[6] suggests that the earliest example of modern citizen science is probably the Christmas Bird Count run by the National Audubon Society in the USA since 1900. Similarly, the British Trust for Ornithology has coordinated amateur birdwatchers to collect scientific data on bird numbers since 1932. The large community of amateur naturalists has made a major contribution to environmental monitoring[7,8].

The term “citizen science” was coined independently and almost simultaneously by Alan Irwin, who positioned citizen science within sociological research and emphasised the benefits of a two-way dialogue with citizens, and by Rick Bonney, who recognised the educational benefits of science communication delivered through citizen science.

1.2 Technology unleashes the power of the citizen

The increasing number of projects and the growing availability of supporting technology have increased the public's ability to participate in science. People can record and analyse data online, use smartphones and apps to capture digital photographs, track their geographic location, measure acoustic information, and increasingly, record temperature and biometric information. Environmental sensors, either as plug-ins to smartphones or as discrete portable or in situ instruments, are available at affordable costs. These can: facilitate species detection (e.g. iBat[9]); measure chemicals or radiation (e.g. Radiation Watch[10]); and monitor meteorological phenomena (a wide range of models; for example the Maplin N96GY[11]).

Such technological advances have tended to benefit citizens most in the developed world; however pioneering projects have sought to use new digital technologies to support and empower people from the developing world, including indigenous communities (e.g. Sapelli[12], a new mobile platform for data collection designed for non-literate users with little or no experience of computing technologies).

The home computing revolution has supported 'volunteer thinking', with projects crowdsourcing the human ability to recognise patterns to classify anything from galaxies (Galaxy Zoo[13]) to cancer cells (Cell Slider[14]), and 'volunteer computing', where people "donate" spare computer processing capacity to support analysis of large datasets (for example, Weather@home[15], which creates state-of-the-art climate models). Online engagement can also support awareness-raising and education, and participants can join groups, ask questions and even create their own projects and networks.

1.3 What motivates amateurs to get involved?

Citizens' motivations for participation include but are not limited to: learning about and discovering the world; contributing to a real-world issue and scientific endeavour; satisfying their curiosity; achieving a personal ambition; and scoring reputational points. Indeed, enthusiasm for citizen science ranges from altruistic desires to give something back to nature and/or their community, to engaging in an activity or project that they are passionate about, emotionally connected to and/or which is fun[16,17]. Citizen science also offers practical benefits: participation may contribute towards educational qualifications and valuable career

experience, and citizens can be financially incentivised to participate, as well as take great pleasure in the 'gaming' element of competition.

1.4 What can citizen science do for the world?

There is a growing consensus that a citizen science approach is well suited for tackling global issues. In their broad-ranging guide to citizen science, Tweddle et a1.[18] conclude: "*One of the core strengths of the approach is that it can be used to present global issues – such as the impacts of climate change or biodiversity loss – in a way that is locally relevant and meaningful*."

(a) Provide useful data

Citizen science has the power to collect vast quantities of data. Roy et al.[19] reported that volunteers generate approximately 85% of the species-level biodiversity monitoring data required by one government body. 'Gentleman naturalists' who kept meticulous scientific scribblings on everything from finch beak sizes to precipitation in their back garden have now been joined by an army of citizen scientists equipped with everything from accelerometers (detecting imminent earthquakes in their region, e.g. Quake-Catcher Network[20]), to audio sensors (measuring noise pollution in their neighbourhood e.g. Royal Docks Noise Mapping[21]) to geo-location devices (monitoring the seasonal arrival of red admiral butterflies e.g. Nature's Calendar[22]), all in the pursuit of scientific advancement.

Citizen scientists around the world have discovered unusual 'Green Pea' galaxies[23] and informed us that once common species of bumblebee in UK gardens are in decline[24]. The environment is one such research area that is relatively well represented among citizen science projects because participants can collect data over wide geographic scales, long temporal scales and on private property. This magnitude of data collection would not be achievable by professional scientists alone. A comprehensive review of citizen science as a research too1[25] provides a vast array of examples of projects that tackled large-scale issues ranging from climate change to ecosystem ecology. There are many projects that survey areas that are relatively inaccessible to professionals; for example, domestic gardens represented a quarter of the 4,200 sites surveyed in OPAL's Soil and Earthworm Survey[26]. As a result, citizen science has helped to produce a very large number of peer-reviewed papers. Galaxy Zoo alone has produced 30, many of which are highly-cited in their field[19].

The importance of citizen-collected data is acknowledged by policymakers and has been cited in management plans and research strategies[27,28] as a means to support official capacity in the designation of protected areas, environmental impact assessments, environmental indicators and identification of invasive species. Of course, data quality remains one of the principal concerns where data is derived from non-professional scientists. This should not be ignored or downplayed but instead understood, monitored, and, where possible, improved. In some cases however, non-

professional and professional scientists can yield very similar ecological results; for example, for detecting species diversity[29] or identifying species [30], where indeed Cooper[31] cites over 50 peer-reviewed studies which investigate data quality. (Data quality is explored further in 3.3.)

(b) *Spark awareness, bring education to life and provide other community benefits*
Citizen science engages people with science concepts and familiarises participants with scientific language, and raises awareness of the vital environmental issues facing society. These benefits have been recognised by policymakers in the UK (e.g. Defra's Chalara Management Plan[27]) and further afield (e.g. the European Union Biodiversity Strategy[32] and the European Commission report on Environmental Citizen Science[5]).

Public engagement in research through activities like citizen science has the potential to support wider social and community-based benefits, such as a stronger sense of community, a greater sense of purpose, health benefits from being outdoors, an enhanced connection with nature and a sense of environmental responsibility[33]. There is also evidence that citizen science can benefit particular demographic groups such as children, and people who are unemployed, disabled, homeless, retired, or from socio-economically deprived backgrounds[33]. Citizen science projects can be designed to address environmental, economic and social justice issues. Marginalised women, for example in less-developed countries, could, in theory, work with professionals to address environmental issues that affect their livelihoods and homes in order to find solutions, seek redress and consequently improve their prospects and those of the environment.

(c) *Empower greater participation in decision-making towards improved environmental justice*
Citizen science can provide a good opportunity for people to advance positive environmental change or solve issues. Citizens can collect both anecdotal and fact-based evidence, which may be supported by other professional data and analysis. Such evidence can help to advance environmental justice, particularly where there is an absence of 'official' data (from a local authority or regulatory body etc.) or perhaps by acting as a quality control mechanism for official data.

Within environmental decision-making, citizen science can take a collaborative or confrontational form[34]. In the collaborative form, public participants work together with other stakeholders to collect information about local conditions; in the confrontational form, however, community mobilisation to generate evidence around environmental issues and social inequalities may challenge certain interests (for example Mapping for Change[35] supported the work of local residents in Deptford London to measure and map noise levels and air quality around a scrapyard). Whether collaborative or confrontational, citizen science provides scope for collective action,

personal and communal empowerment, and the ability of the community to hold government and corporations accountable. It may also help to move discussion from opinion to the realm of identifying facts and comparing results to known standards.

(d) *Cost effectiveness, efficiency and added economic value from citizen science*
Citizen science is not free science. Substantial investment is needed to develop resources, to recruit, train and retain staff and participants, and to support the necessary information and communications technology infrastructure integral to many projects. However, this investment can pay dividends. First, compared to the costs of employing government officials or expert scientists, using volunteers can be highly cost-effective. Professional scientists in turn benefit from the data submitted by volunteers, the value of which can be estimated at many millions of pounds per year[36]. For example, investment from government of £7 million into volunteer monitoring schemes generated data estimated to be worth £20 million in in-kind value[37].

Citizen science projects can also accelerate the period from data collection to analysis and dissemination, especially where smartphone technology allows immediate data entry. Using volunteers can also free up professionals to focus on highly specialist activities such as diagnosis and advice. The geographic distribution of volunteers can save costs on travel and associated environmental impacts.

Finally, public participation in citizen science can generate additional economic benefits, such as through retail and tourism. A survey by the United States Fish and Wildlife Service estimated the annual economic value generated by bird and wildlife watchers at around US$32 billion per year in retail sales and US$85 billion in overall economic output, producing US$13 billion in State and Federal income taxes, and creating 863,406 jobs[38]. Policymakers may then have another motivation for supporting the growth of citizen science.

2. Applying citizen science to the nexus

The global challenges humanity faces in the next 100 years are truly alarming: more than a billion people are without secure food supply and have only limited access to clean water, sanitation and energy; natural resources are being over-exploited; and ecosystems and the services they provide are being degraded[39]. Pressure on these resources will only increase given population growth, urbanisation, climate change and globalisation of trade. Hoff argues the main challenge is to reconcile long-term global objectives of climate protection, ecosystem protection and social equity with immediate economic benefits, local livelihoods and access to water and food. He champions the nexus approach "to enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across [the nexus] sectors"[39].

Citizen science offers an opportunity to engage policymakers, businesses and the public in nexus issues. Citizen science activities may also provide a means to create connections and build relationships between different players across nexus life-cycles, such as between urban populations and rural suppliers of services and goods; or recipients of food imports and producers in exporting countries; or citizens and researchers in social, economic and natural sciences; or even between policymakers in different government agencies responsible for different nexus issues. Exploration of the nexus through citizen science has the potential to contribute to a range of nexus needs.

2.1 Data and evidence

There is an increasing need from governments and scientists for long-term data to monitor nexus-related trends. Citizen science has proven potential to collect data against a range of indicators and metrics associated with nexus issues, in particular in relation to the impacts of food, water and energy on the environment. Picking three examples:

- Water pollution, from exploring metal contamination of lake and pond sediments[40], to students assessing the impact of sand and gravel mining on drinking water quality in Maine, USA[41].
- Climate change, either directly through meteorological measurements or indirectly through phenology, spread of new species and the loss of indigenous species (e.g. Nature's Calendar[22], a phenological investigation into the impacts of climate change; or the Floating Forests Project[42] that asks participants to monitor kelp canopy changes by reviewing satellite images, and also aims to assess associated carbon sequestration value).
- Degradation of natural resources, such as through monitoring desertification, deforestation, or carrying out soil assessments (e.g. ForestWatchers[43] invites citizens to clean satellite imagery and identify areas of deforestation, or the OPAL Soil & Earthworm Survey[44], where participants carry out simple chemical, physical and biological assessments of soil, and which has demonstrated that citizen-generated data could prioritise soil assessment with a view to addressing the concerns and objections to soil protection policies[45]).

Other data could support early warning systems for the crossing of critical thresholds or the impact of new agricultural or industrial processes, such as intensification of food production or new energy infrastructure. While citizen science can collect "simple" data, the nexus involves complex connections across water, energy, food and the environment, and collecting data across these areas presents challenges to any investigator, whether professional or citizen scientist. A number of approaches to citizen science could generate useful data to fill knowledge gaps and investigate more complex nexus issues.

(a) Citizens can support the development and management of complex monitoring networks

Citizens can support monitoring networks around nexus issues and their involvement can enhance their design and support their operation. For example, a report by Zemadim et al.[46] outlines the development of hydrometeorological monitoring networks in the highlands of the Blue Nile River Basin of Ethiopia. Citizens' lay knowledge of, for example, the hydrological characteristics of watersheds or other features, such as flood-prone areas or land used for cattle, was key to inform the design of equipment and identify the best safe and accessible locations for their installation. Data was automatically collected but citizens also manually collected data on a daily basis, and findings were fed back to communities. The research provided assessments of current land management interventions and recommendations for new rainwater management interventions.

Monitoring networks supported by citizens could explore a range of nexus issues. Local weather monitoring networks inform all nexus functions and could provide better understanding of urban weather and the urban heat island effect in the context of green cities or support better planning of renewable energy infrastructure. Sensor networks across aquatic ecosystems could perhaps provide a better understanding of river flows to support more effective hydropower generation.

(b) Citizens can contribute to participatory planning and design

Citizens can contribute to geographic planning and the design of technology. Such involvement may also reduce tensions between stakeholders. For example, following significant declines in groundwater underlying the Umatilla basin (in Oregon, United States), consultation was held with a wide range of citizens including irrigators, residents of rural, city and Tribal areas, scientists and consultants, and a taskforce was formed and charged with the responsibility of delivering short-term solutions and a plan for sustainable current and future water management. Together they developed a plan with support across all users that met broad community groundwater needs until 2050[47]. Another example is the NOVA Energy Lab[48], which is an online platform that supports the public to 'design a renewable future' for a US city at the lowest costs possible by engineering a system that uses solar, wind and hydroelectric energy sources.

(c) Citizens can support the monitoring and valuation of ecosystem services

Scientists and politicians refer to the goods and benefits we derive from our environment as 'ecosystem services'. While it is easy to put a market value on some goods such as food and minerals, society largely takes other benefits such as clean air for granted and underestimates their value. Understanding the true value of all these benefits and the potentially damaging consequences of processes such as energy production, agricultural intensification and water desalination is essential. Through monitoring simple metrics (such as those noted above), citizens can monitor ecosystem services such as air or water quality regulation; with appropriate tools they can calculate carbon sequestration values; and with guidance they can give their own estimations of the value of the 'cultural' service provided (e.g. through recreation, as heritage, or the physical and mental health benefits provided). Detailed valuation of particular ecosystem services may demonstrate that some are more efficient and more cost-effective to maintain than hard infrastructure (e.g. water processing plants) or end-

of-pipe solutions (i.e. where contaminated water or air is cleaned at the point it enters the environment). Engagement between 'nexus researchers', policymakers and citizen science practitioners would support an assessment of citizens' ability to deliver against evidence priorities.

2.2 Engagement and awareness raising

The principal benefit of exploring nexus issues through citizen science is that while increasing the provision of much-needed data, it simultaneously raises awareness of the issues and their connections, and starts to create a cadre of environmentally-literate people who can take greater responsibility for the environment and contribute to policy development.

Participants may adopt more sustainable lifestyles, for example through:

- changing their daily practices, such as the temperature they wash their clothes at;
- making more effort to reduce waste at home and encouraging retailers to do likewise (e.g. less packaging for food);
- adjusting their shopping habits to take account of food miles and virtual water (i.e. the flow of water from one region to another through exported commodities, such as food).

Implementation of a citizen science element to engage the public in nexus issues should not preclude the use of other, more conventional methods. Involvement in a citizen science project may be the first step a citizen takes in engaging in a nexus issue, but any interest and enthusiasm generated should be encouraged by identifying potential follow-on activities, such as opportunities for civic participation, further training, or informal or formal learning. Equally, participation in a citizen science activity may come as a later step, after having their awareness of the nexus issue raised through some other means. Participation in citizen science could inspire a new generation of scientists, regardless of when in life they come to the profession.

2.3 Support greater involvement in management and governance of nexus issues

Citizen science can support greater participation in environmental decision-making (see 1.4(c)). This is especially important in the context of the nexus because the trade-offs between energy, food, water and the broader environment present a complex network of stakeholders. Citizens must be empowered to have a voice here. Citizen science enables citizens to collect their own evidence, transforming them from research subjects or passive receptors of education to protagonists on a more equal footing with scientists and policymakers. It may enable participatory planning (see 2.1.(b)) or contribute towards participatory democracy and environmental activism leading to improvements to social

equity and environmental justice, reflecting the human-rights based approach of the 'Green Economy'. This is likely to be especially relevant in developing countries. Citizen science also has the potential to support social change: citizen-generated data could be used to provide evidence to support the kind of citizen journalism and political action seen, for example, during the Arab Spring.

2.4 Co-creation – putting citizens in the driving seat

The majority of citizen science projects developed so far have arisen from research questions generated by professional research or policy needs. In contrast, problems posed by the nexus include trade-offs affected by consumer choices and business supply strategies. For this reason, a citizen science approach to the nexus would likely be most successful where it invites participation from citizens and firms (2.5) in designing activities.

Inclusivity is important: nexus issues affect everyone, rich and poor, and so citizen science on the nexus must be sure to engage all parties, whether they are producers or consumers in the Global South or Global North. It has been reported that, in bird-watching programmes for example, more affluent, scientifically literate people are the most likely to participate in citizen science[49, 50]. Although this is a key audience, and they are likely to be key influencers of change, great efforts must be made to involve people from less affluent communities (where individuals often live in areas of lower environmental quality) and less developed countries (who may be most directly affected by the consequences of nexus issues). Care should also be taken to ensure that activities attract both men and women as different activities may appeal to different genders (for example, more competitive activities may appeal more to men than to women[51]). Evidence has shown that the most disadvantaged communities can participate in citizen science if properly supported[33], including those in less developed countries[52]. Recent research reveals how citizen science can facilitate a re-engagement with science for individuals who last studied the environment at school[8]; it also identifies how citizen science can extend the interest areas of already-engaged amateurs, which could help to mobilise, say, already enthusiastic natural historians to investigate new subjects associated with the nexus.

Citizen science that is co-created or entirely citizen-led may have the most powerful potential for promoting environmental justice. Towards this, the UCL Extreme Citizen Science research group (ExCiteS) develops methodologies and tools to allow "a situated, bottom-up practice that takes into account local needs, practices and culture, and works with broad networks of people to design and build new devices and knowledge creation processes that can transform the world"[53]. This approach allows local citizens to take the lead on local issues and use techniques and methods that fit local conditions, and therefore are more likely to be used for longer. It includes providing simple tools that can be used by a wide range of participants, who are involved also in the analysis of the data and deciding on the course of action that should be followed. Involving citizens directly in the project at all stages is likely

to achieve greater public engagement and may result in participants feeling more able to engage in decision making based on data derived from their efforts.

Recommendation 2	A co-created citizen science approach is likely to be more appropriate both to address the more complex nexus issues and to engage all sectors of society (inclusivity).

2.5 Taking citizen science into the boardroom

There are many reasons to support greater and earlier involvement of businesses in citizen science engaged with nexus issues. Businesses can operate at a multinational level which is useful to address the transition of citizen science from a local to global level (see 3.1 below); they are at the forefront of technological developments; and they are well-placed to change practices to reduce harmful impacts.

Businesses are already supporting citizen science activities, such as the Big Bumblebee Discovery[54], funded by the energy provider EDF, and which supports schools to explore the relationship between bumblebees and their local habitat. Business involvement might form part of corporate social responsibility commitments, but there could be opportunities for introducing citizen-collected data to inform strategy or operations, to develop or test new technology, or to support research and provide evidence for policy. Through participation in citizen science, firms may identify efficiencies in systems and services, reduce or provide early warning of environmental impacts (potentially avoiding expensive legislation), or gain a better understanding of their customers.

One example of a business-led citizen science project is being developed by Arnia[55], a company which develops monitoring equipment for beehives, with technology that captures data such as hive temperature, humidity, weight and meteorological conditions, with acoustic sensors to monitor and interpret colony behaviour, strength and health. Arnia's proposed citizen science programme seeks to understand the status and dynamics of bee populations by engaging beekeepers to collect, interpret and share data with a wide range of research institutions. As the developers of the technology, Arnia is able to donate equipment to build a large network. With existing relationships with beekeepers and an international customer base Arnia could support monitoring at geographical scales never previously undertaken (UK-wide with possible extension to Europe and the US). Current plans for funding the project are through a mixture of corporate sponsorship, crowdfunding and contributions in-kind. Grant funding from public bodies, a more traditional source of funding for citizen science, could extend engagement beyond beekeepers to the wider public (for example, through a programme engaging schools), increasing the project's impact. However, pathways towards such funding are not immediately apparent and SMEs may need further guidance or support.

It should, however, be acknowledged that the promotion of citizen science may be counter to the interests of businesses. The example cited of Arnia is a company whose business

operations do not have any significant environmental impact and whose interest to better understand the environmental pressures on bees aligns closely with government policy and public sentiment. This will not be the case for all businesses and there is the potential for tensions and possibly conflict between groups around the nexus (see 3.2, 3.5 and 3.6 below).

Recommendation 3	Mechanisms for engagement with businesses need to be developed.

3. Issues and challenges

Citizen science is not without challenges and using it to investigate the nexus is likely to create some new nexus-specific issues. To date, citizen science has tended to operate in a less-politicised realm (not in all cases), but with the nexus would be entering into more complex political dynamics.

3.1 Scale – from local to global

Citizen science's connection to neighbourhood and engagement with local people makes it particularly powerful at generating data at a local scale, and increasing awareness and understanding of local environmental issues[49]. To engage with the nexus, however, the local scale benefits of citizen science need to be transposed to regional and global scales. A shift in scale may affect citizens' motivations for taking part. Different scales may also pose funding challenges (see 3.8 below). Scaling up citizen science to operate across state and political boundaries will require standardised methodologies with toolkits and best practice guides to ensure consistency. The interoperability of systems relating to data verification and validation, data storage and access, and metadata will need to be improved. These are not insurmountable issues and work is under way from the two newly-created citizen science associations, the European Citizen Science Association (ECSA)[56] and the US-based Citizen Science Association[57]. For example, ECSA promotes engagement with INSPIRE[58], a European Directive aiming to integrate environmental spatial data across Europe to improve data sharing across the public sector and facilitate open access to data. Although current membership of these associations tends to be largely (but not exclusively) around biological monitoring topics, researchers of nexus-related issues are welcome to participate.

Recommendation 4	Through participation in the nascent international citizen science associations, ‘nexus scientists’ should share research and evidence priorities, contribute to the development of international standards, and co-ordinate relationship-building with international policymakers and scientists.

Drivers from the developed world, such as demand for resources, may significantly affect the developing world but consumers may be unaware of the 'true' cost of their impact. One

potential approach could be developing citizen science projects with multi-scale engagement of citizens. For example, a pilot project completed at UCL and currently seeking full funding was carried out by the ExCiteS research group seeking to assess the potential of indigenous knowledge and smartphone technologies to challenge 'land-grabbing' in Ethiopia and secure indigenous rights. Large-scale land acquisition for resource extraction has led to the displacement and impoverishment of indigenous people, in particular of traditional pastoralists. The project would use the Sapelli software (see 1.2 above) on rugged smartphones to document indigenous land use and strengthen claims by creating maps for governments and foreign investors. Support for these indigenous claims could be increased through engagement of citizens across the developed world. Projects such as ForestWatchers (see 2.1) demonstrate that volunteers from across the world can contribute via their computers to monitoring the deforestation that may be associated with land-grabbing, providing citizens in Ethiopia with greater surveillance of land changes, and ExCiteS is coordinating with the World Resource Institute (WRI) in an effort to use their Global Forest Watch platform to support indigenous data collection. Another relevant crowdsourced approach could include classifying images captured by camera traps to monitor the impact on local biodiversity of land use changes. By combining the co-created approach of ExCiteS and the crowdsourcing approach of more internationalist projects, citizens at both scales could be engaged. With the introduction of information exchange between them, relationships could even be built between the different groups.

Increased understanding in citizen scientists in the developed world of the environmental pressures faced by citizens in the developing world could lead to changes in consumption habits and other behaviours or encourage social/political action, such as lobbying companies to change their practices. Engagement at multiple scales could also facilitate investigation of more complex nexus issues operating at wide geographic scales, for example providing full life-cycle assessments of water and energy use, or perhaps monitoring environmental impacts or waste across a supply chain.

Recommendation 5	Citizen science practitioners and nexus scientists should explore developing citizen science programmes with multi-scale engagement of citizens, for example programmes focusing on a nexus issue that combine local, citizen-led or co-created projects to make best use of local knowledge and expertise, with computer-based, volunteer-thinking projects engaging citizens around the world.

3.2 The challenges of engaging businesses

Although participation in citizen science could have a range of benefits for businesses, the empowerment of citizens by enabling their collection of environmental data could be detrimental to business interests. For example, increasing public awareness of nexus issues could reduce consumption, result in new regulation requiring high-cost mitigation measures, or result in expensive litigation. The potential need for open access data may conflict with

protecting business sensitive data or compromise patents and research and development of new technology. Greater involvement of citizens has potential to create conflict with businesses, for example where they are monitoring evidence about problems associated with industry in their area (e.g. see section 1 on the impacts of drilling in Peru). Data on citizens' consumption habits of food, water and energy will be of value, but transparency regarding why data is being collected and how it will be used is essential (see 3.5). Given these issues, greater understanding of the motivations for business involvement should be sought (see 3.6 below).

3.3 Is the quality of citizen-collected data fit for purpose?

Data collected by amateurs will inevitably come under greater scrutiny than those collected by scientists and thus raises questions regarding data quality in citizen science. The expertise, skills, enthusiasm and commitment of citizen scientists is highly variable and with such vast numbers of often unknown participants contributing, challenges naturally exist if data is to be fit for purpose[59]. This may restrict the application of a citizen science approach to some areas of data collection. Some studies[30,45] have shown that data collected by large-scale citizen science projects can highlight broad-scale trends but not necessarily pick up detailed observations. These broad-scale trends, however, could be important for nexus issues. A study by Peckenham et al.[41] demonstrated that school pupils in Maine, United States, were able to monitor groundwater samples just as well as the experts for some parameters such as pH and conductivity, but not all of them, highlighting that careful selection of study variables is important.

Careful consideration of the previous experience and level of skill of the public participants together with sustaining their enthusiasm will ensure activities are designed at an appropriate level and carried out to the best of participants' abilities. Various approaches can be employed for data validation (and projects which employ multiple approaches enhance quality further), including: automatic filtering of unusual reports, automatic recognition techniques, submission of samples or of photographic evidence of species observed, novel statistical techniques to assign correction factors to observer error (for a comprehensive review see Wiggins et al.[59]). No matter what validation methods are used, attention to monitoring data quality is essential to ensure that data users are aware of the associated level of accuracy and are therefore able to determine whether it is fit as evidence for their purposes.

3.4 Data sharing

In order to maximise the benefits of the data gathered by citizen scientists, and reflect its public origin, there is a drive to make citizen science data open access and widely available. However adherence to this principle can be challenging as:

- funding terms or other conditions on intellectual property rights may restrict data sharing;

- stakeholders may not want all data shared or delay sharing data because the status or kudos is conferred by being the first to discover phenomena;
- there may be restriction on sharing sensitive data, e.g. to protect the locations of rare or endangered species or citizens' personal data;
- inconsistent data standards may also limit data sharing.

The importance, sensitivity and scale of nexus issues and the increased number of stakeholders are likely to exacerbate the data-sharing challenges. The openness and immediacy of data has the potential to challenge official policy, business operations, and traditional publication restrictions of funders and academic institutions. However, support for the principle of sharing data is strong. The UK Government[60], NGOs such as the Open Data Institute[61] and EU-wide projects such as Socientize[62] are all working towards greater sharing and freedom of data, allowing it to be used for the greater good.

3.5 Transparency

Citizen science may be thought of as having fewer ethical issues than normal scientific investigation because participants make an informed choice about their level of involvement and can normally stop at any time. However, projects must ensure that their aims are clear. This transparency may become even more important when investigating nexus issues as a particularly valuable area for scientific investigation using citizen science is the domain of food, water and energy consumption practices. Care must be taken that willing citizen scientists are not unknowingly turned into research subjects. Actual and perceived risk may be heightened where businesses are a key stakeholder in projects and the data collected provides opportunities for market testing. Transparency regarding why data is being collected and how it will be used is essential. To further safeguard citizens, particularly where the development of projects identifies tensions, consideration should be given to introducing some form of contract between stakeholders, setting out agreed use of data and other commitments between parties.

Recommendation 6	Where tensions are identified, citizen science projects should consider introducing some form of contract or agreement setting out responsibilities between stakeholders, including use of data.

3.6 Motivations of 'nexus players'

The motivations of public participants in citizen science have been discussed previously (see 1.3), but the motivations of policymakers, researchers and businesses are not well understood. While altruism is a motivator for some individuals and businesses, as noted there may be tensions around reduced profitability or other issues detrimental to their interests. In some cases, organisations that operate with a strong social mission (social enterprises) might be suitable hosts to develop and run citizen science (for example, Mapping for Change, see 1.4(c), is a social enterprise). Barriers to citizen science are also likely to exist among

policymakers and researchers. Policymakers may fear that they will lose control and some are likely yet to be convinced about the quality of data derived by 'amateur' rather than 'professional' scientists, despite evidence to the contrary (see 3.3). In addition to concerns about data quality per se, Riesch and Potter[63] report that professional scientists are also worried about the reaction of the wider scientific community (such as journal peer-reviewers) and even on the potential harm to their careers from participating in citizen science projects. Exploring shared motivations and concerns is important to engaging all nexus stakeholders (including the public) in citizen science.

Recommendation 7	Research is needed to understand the motivations, attitudes and willingness to change behaviours across all nexus stakeholders, and to better understand and find solutions to barriers.

3.7 Communication across an increasingly complex network

Communicating across firms, scientists, policymakers and citizens at local, regional and global scales will present challenges, particularly where co-created citizen science projects are considered desirable. A mixed communication and engagement approach will be required combining traditional approaches (e.g. websites, workshops, media) with innovative social media and new technology.

Although not a means to engage directly with hard-to-reach groups (who may have less access to computers), web-based approaches may assist to create a virtual community of interested citizens. One novel application worth considering is the use of SISWEBS (Scientific Information Syndication WEBsiteS), a collection of free, collaborative websites which employ social bookmarking and syndication techniques (e.g. tagging, flagging, voting, user-based ranking, commenting) to track users' behaviours in real-time and their correlations with other users' characteristics and societal/external factors (e.g. occurrence of a flood can increase interest in flood-related information) to highlight what is new and popular. Citizens are the editors; collectively and democratically, they decide what is popular and interesting by voting on and ranking posts. SISWEBS differ from popular social bookmarking/networking websites such as Twitter and Facebook as each SISWEB is dedicated to a particular scientific subject. Users share their knowledge, opinions and bookmarks resulting in improved education and research benefits. WaterSISWEB[64], a community dedicated to water resources, was the first member of the SISWEBS family. Launched in May 2008 by a group of University of California-Davis students, it has since attracted users from more than 200 countries, who have posted over 20,000 links.

A SISWEB focused on citizen science, publicised and marketed to citizens, scientists including nexus researchers, and businesses could provide a means to engage stakeholders across the nexus. SISWEBS has recently started collaborating with Imperial College London and will be launching an integrated group of new SISWEBS on different topics such as the

environment, climate change, energy and sustainability in the near future. The SISWEBS project leader (Kaveh Madani) is a co-author on this paper.

Recommendation 8	Examine the feasibility of a SISWEB approach to engage and communicate with citizens, businesses and scientists on citizen science, including its potential to investigate nexus issues.

While there is a desire to support more citizen-led projects, it should be acknowledged that these citizen- rather than scientist-led projects tend to arise spontaneously and include groups who may not have existing relationships with, or access to, networks of citizen science practitioners (many of whom are university-based) from whom they can access learning, technology and good practice to support their objectives. These groups may not have access to computers to be engaged via online means. Citizen science practitioners then should seek to reach out to a wide range of other actors in the areas of their interest, including NGOs, charities, social enterprises, and other civil society organisations.

Recommendation 9	Citizen science practitioners and nexus scientists should engage with a wide range of NGOs, charities, social enterprises and other civil society organisations in order to make contact with citizens affected by nexus issues and support them to lead their own citizen science projects.

3.8 Funding and capacity challenges

Most citizen science projects are funded by grants from governments (including agencies and research councils) or third sector organisations (e.g. NGOs, charities). Most of this funding is available at national levels, with some mechanisms (e.g. European Commission Horizon 2020 programme) available at regional levels. There is a funding challenge to scale up programmes to engage with nexus issues at international levels. Not a problem unique to citizen science projects, funding tends to be time-limited posing challenges for financing the longer-term monitoring that some nexus issues require. In the context of citizen science, this may also affect participant motivation.

One citizen-led approach for generating funding for citizen science projects would be crowdfunding or membership organisations. Due to scales of investment, grant funding from traditional sources will likely remain essential, however crowdfunding or member subscriptions may provide a useful supplement, perhaps extending projects over longer periods, or providing a more organic response to citizens' priorities, or facilitating speedy creation of new projects in response to spontaneous environmental justice issues. Incorporation of this function into a SISWEB, where participants flag their support for ideas for citizen science activities investigating nexus issues may be an effective way to select projects to be put forward for crowdfunding.

Recommendation 10	Citizen science practitioners should explore crowdsourcing to

	identify citizen science projects on the nexus and then crowdfunding as a primary or supplementary source for funding the project.

Citizen science practitioners have demonstrated a willingness to be early adopters of new technology and innovators of existing technologies. Together with volunteer effort, this has enabled citizen science practitioners to deliver a lot of science on, at times, very little budget. This added value from a citizen science approach will be essential to exploring more complex problems posed by the nexus, especially over the geographic scales of nexus problems. Citizen science practitioners should continue to build relationships with technology communities in order to access new technologies as early as possible. An increasing commitment to open access data and open source technology would support collaboration with a wide range of groups. For example, hackathons, where computer programmers and other specialists involved in software development (e.g. graphic designers) are invited to solve a problem, have already been used successfully to support citizen science. Another example group to engage with is computer gamers, as the benefits of "gamification" for engagement and repeat participation in citizen science activities is also recognised. An appropriate portal for engagement, such as a SISWEB, together with willing ambassadors reaching out across digital communities would enable citizen science to remain at the cutting edge of technology.

Recommendation 11	To increase capability and extend the reach of citizen science to the nexus, citizen science practitioners should engage with a wide range of technical communities to remain at the cutting edge of new technology.

4. Conclusions

1. Citizen science offers a flexible approach to engage all stakeholders (researchers, policymakers, businesses and citizens) across nexus issues (water, energy, food and the environment).
2. Citizen science, particularly when using a citizen-led approach, can raise participants' awareness of complex nexus issues, while also providing educational value and enabling increased citizen involvement in the political process and their ownership of solutions.
3. Data provided through citizen science can be reliable, although attention must be paid to quality control and for some purposes citizen-collected data may not be suitable. A citizen science approach may enable collection of data across a wide range of indicators associated with environmental impacts around the nexus and, through participatory planning and involvement in monitoring networks and ecosystem services assessments, citizens may be able to support investigation of more complex nexus issues.

4. Greater involvement by firms in citizen science should be sought because they often operate at the scales of nexus issues (e.g. across regions and continents) and are often best positioned to drive technological innovations to solve nexus problems.
5. The main challenges likely to be encountered when using citizen science to address nexus issues are scaling-up activity from local to global levels, securing involvement of businesses, rationalising increasingly complex data issues, understanding the motivations, attitudes and practices of all participants (in particular to avoid conflict and to ensure transparency), communicating effectively across an increasingly complex network, and securing and maintaining funding for projects.
6. Nexus players are best placed to consider the feasibility of exploring the nexus through citizen science. One possible next step would be a workshop of nexus players and citizen science practitioners to explore the citizen science approach and perhaps, through development of a pilot exercise, examine whether a multiscale application of citizen science (local, co-created projects combined with crowdsourced, international projects) could be used to create a programme spanning international borders in terms of both participation and the nexus issues investigated.

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