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The role of citizen science in addressing grand challenges in food and agriculture research

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The power of citizen science to contribute to both science and society is gaining increased recognition, particularly in physics and biology. Although

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there is a long history of public engagement in agriculture and food science, the term 'citizen science' has rarely been applied to these efforts. Similarly, in the emerging field of citizen science, most new citizen science projects do not focus on food or agriculture. Here, we convened thought leaders from a broad range of fields related to citizen science, agriculture, and food science to highlight key opportunities for bridging these overlapping yet disconnected communities/fields and identify ways to leverage their respective strengths. Specifically, we show that (i) citizen science projects are addressing many grand challenges facing our food systems, as outlined by the United States National Institute of Food and Agriculture, as well as broader Sustainable Development Goals set by the United Nations Development Programme, (ii) there exist emerging opportunities and unique challenges for citizen science in agriculture/food research, and (iii) the greatest opportunities for the development of citizen science projects in agriculture and food science will be gained by using the existing infrastructure and tools of Extension programmes and through the engagement of urban communities. Further, we argue there is no better time to foster greater collaboration between these fields given the trend of shrinking Extension programmes, the increasing need to apply innovative solutions to address rising demands on agricultural systems, and the exponential growth of the field of citizen science.

1. Introduction

Citizen science, which we define broadly to include research in which non-scientists play a role in project development, data collection, or discovery and is subject to the same system of peer review as conventional science [1], has been around for centuries, but it has received renewed attention in the last decade. This is partly because of the recognition that engaging citizens in science can speed scientific discovery, democratize engagement in science and, potentially, improve or influence the decisions stakeholders make in light of science. Citizen science data are now commonplace, though the term 'citizen science' is often not explicitly used. For example, the majority of data used to understand how migratory birds respond to climate change were collected by the public, and yet none of the papers relying on these data used the term 'citizen science' [2]. This incongruity is particularly obvious in the food and agricultural sciences; less than 2% of the 2 077 indexed (Web of Science) studies using the term 'citizen science' also use the word 'agriculture.' However, this does not mean that citizens play little role in food and agricultural sciences. On the contrary, citizen science has been a part of agriculture for millennia. For example, in China, observations of locust outbreaks by the public date back approximately 3 500 years [3]. Indeed, based on our definition of citizen science, there is probably no richer set of historical examples of activities resembling citizen science than there is for fields related to agriculture and food science.

Historically, connecting members of the public engaged in agriculture, principally farmers, and scientific research has been a role of extension. Land-grant universities in the United States were formed by the Morrill Act, in response to rapidly changing agricultural practices [4]. The Smith–Lever Act added Extension services to the mission of land-grant universities. In the context of agriculture, the missions of extension are to bring science and technology to farmers and food producers and to learn about new observations and problems from those stakeholders. This bidirectional flow of knowledge itself is not citizen science, but it creates an opportunity to do citizen science—generate new knowledge, through partnerships between scientists and the public. A farmer might note a new pest and contribute data about the observation of that new pest to a university Extension agent or a scientist. The scientist then connects that observation (a data point) to the broader scientific literature and offers back to the farmer context about the observation and, hopefully, a solution if appropriate. Scientists not only engage farmers as data collectors, but also as collaborators guiding research responsive to daily needs. In this way, extension facilitates what many in the field of citizen science would consider citizen science at its best.

Although only recently emerging, the field of citizen science has undergone rapid growth. With that growth has come a wealth of knowledge, ideas, and insights related to effectively engaging the public in scientific research. Yet, this recent rise in interest and development of citizen science tools and networks has not taken full advantage of the potential of extension in the agricultural sciences. Similarly, fields related to agriculture and food science have not taken full advantage of the tools and knowledge being generated in the field of citizen science. This is unfortunate, given these fields share many similar goals (e.g. foster bidirectional exchange of information, democratize science, engage stakeholders or communities, and enhance scientific impacts). Thus, there remains enormous potential to broaden the overlap between these fields through greater communication as well as build from where they already overlap through collaborations that leverage the infrastructure of each of these fields.

An important initial question is: why should we bring together citizen science, extension, and food systems now? There are at least three major reasons. The first reason is pragmatic. Funds available for extension are decreasing [5], especially for international extension, e.g. Centre for Agriculture and Biosciences International (CABI) or International Center for Agricultural Research in the Dry Areas (ICARDA). At the same time, food system challenges are increasing, both because we must feed more people—perhaps a billion more globally by 2050 [6]—and because people are ever more disconnected from food in ways detrimental to their health [7]. Thus, we need new approaches to engage stakeholders and the public in the science of food and agriculture, especially in places where Extension is downsizing and there could be a critical loss of experience and infrastructure. The second reason is the increasing globalization of agricultural problems. In a connected world, the movement of pests and pathogens poses increasing threats. A globally connected system is needed in response. The third reason is to fulfil the promise of citizen science. A weakness of most large-scale citizen science is lack of on-the-ground, in-person networks, networks of exactly the sort that extension systems provide. Thus, there lies an opportunity to leverage the strength of Extension—a high geographical density of professionals who can take information generated at a central place (e.g. a university) and disseminate it to help local people tailor information for local solutions.

We convened a working group to identify key opportunities at the interface of extension and citizen science that fully leverage the strengths of each and to consider ways of fostering greater overlap between these fields and the benefits of conjoining these fields. The working group brought together ~50 participants from state agencies, universities, and non-governmental organizations from across the world to share a breadth of research backgrounds, experiences, and perspectives. We considered the unique value agriculture and food offer citizen science and conversely what citizen science offers to engagement/extension in the context of agriculture and food. We report our conclusions as follows: first, we demonstrate how citizen science projects, many of which do not describe themselves as such, are already addressing grand challenges facing our food systems and the broader Sustainable Development Goals outlined by the United Nations, by highlighting the efforts of previous or existing projects. Second, we discuss the opportunities and challenges unique to citizen science as it relates to agriculture/food research, including considering the role technologies (broadly conceived) will play in shaping the future of this field. Lastly, we suggest a series of hypotheses as to the best future avenues for bridging citizen science and agriculture.

2. Role of citizen science in addressing grand challenges in food and agriculture research

There are many threats facing our food and agriculture systems. Here, we focus on citizen science projects addressing some of the greatest challenges in the coming decades: monitoring pests/pathogens, preserving biodiversity and ecosystem services, enhancing food safety, nutrition and flavour, improving food security, and strengthening social justice and education. We do not attempt to provide a comprehensive list but highlight projects that have been innovative and/or successful in their approach.

(a) Monitoring pests/pathogens

One of the grand challenges of agriculture is building local and regional capacities to detect and respond to plant pest problems (insects, diseases, and weeds). Citizen science offers the potential to supplement existing pest/pathogen monitoring efforts by encouraging a culture of sharing observations of pests and beneficial organisms to improve plant health and crop management. Citizen science is already helping to document novel pathogens and pests. For example, citizens are helping provide first reports of pathogens, such as in the case of Sudden Oak Death that was first reported by a concerned citizen [8] and helping to document the movement of pests and pathogens, for example, through projects like Cape Citizen Science (citsci.co.za), where citizen scientists in urban areas monitor plant pathogens in South Africa. These efforts help to improve model predictions of future spread [9,10]. Further, projects like the Mildew Mania Project in Australia (www.mildewmania.com.au) are able to monitor for pathogens such as powdery mildew disease (*Blumeria graminis hordei*) by working with 975 students from 94 schools to grow barley as a bait for the disease.

Often, the data citizens provide to such 'detection and spread' projects are based on photos, much as is the case in extension. Such photos can be validated by experts. In addition, several projects are moving towards the use of software to enable identification of pests, pathogens, natural enemies of pests, pollinators, and other wildlife via cell phones (plantvillage.org, iNaturalist.org). This approach offers the benefit of simultaneously generating data for scientists and being able to link the result, an identification, with information about its control for farmers in real time. Moreover, the public's observations of novel pest–predator interactions may lead to identification and development of potential biological control agents [11] and provide an opportunity to raise awareness about the use of predatory insect communities as an alternative to pesticide use.

Studies in which participants physically collect and submit organisms, rather than simply report observations, provide even greater opportunities for scientists to gather information based on citizen science efforts. Such collections are easier in an agricultural context (than in forests or grasslands) because few species found on farms are protected (e.g. citizens cannot collect insects in Germany, but can collect pest insects). Collection of plant tissue for eDNA analysis can enhance the discovery of microbial diversity [12]. Insect specimens collected by participants are being used to determine global invasion routes and genetic structure of invasive agricultural pests (e.g. the small cabbage white butterfly; pierisproject.org). Similarly, the backyard bark beetle project (backyardbarkbeetles.org) uses beetles submitted by the public to investigate the complexity of fungal symbionts associated with these common forest pests, while participants in the Danish ant hunt (myrejagten.dk) help discover potentially invasive ant species. These projects illustrate the power of collection-based citizen science projects to inform agricultural research and management.

Contributions of participants can also extend beyond observations and collections. For example, participants can conduct manipulative experiments to evaluate different disease treatment methods, such as is being done with the Kauri Dieback Disease that is affecting culturally important forests in northern New Zealand (kaurirescue.org.nz). Other projects use citizen science to help identify plants that may be resistant to pathogens [13]. Both of these initiatives can be replicated and mimicked in agricultural contexts to improve food security and innovate methods of pest and pathogen control.

(b) Preserving biodiversity and ecosystem services

Citizen science is a useful tool for a second grand challenge in agriculture—the need to preserve biodiversity and ecosystem services, whether on farms or adjacent habitats. This grand challenge maps directly onto the United Nation's Sustainable Development Goal (SDG) of achieving environmental sustainability. Multiple projects now focus on biodiversity and associated ecosystem services in an agricultural context.

Many projects facilitate important research about pollination and pollinators (typically bees and butterflies). These projects often link land use to pollination services, whether the focus be on individual species of concern (bumblebeewatch.org) or whole communities (beesneeds.colorado.edu) [14]. Pollinator monitoring projects such as the Great Sunflower Project (greatsunflower.org) and the Ohio Bee Atlas (u.osu.edu/beelab/ohio-bee-atlas) provide vital baseline and long-term data, while also raising awareness of bee diversity and non-target impacts of pesticides (such as bee kills). These outcomes lead to improved understanding of the importance of conserving and creating habitat for pollinators and other agriculturally beneficial insects, such as predators and parasitoids. It is worth noting that while citizen science projects may result in low absolute sampling effort in agricultural landscapes, these landscapes may still end up being relatively oversampled compared to more natural areas due to the lower species richness often found in agricultural landscapes [15].

The number of projects mapping ecosystem services more generally is also growing beyond observational studies of pollinators [16]. Recent studies include experiments designed to quantify ecosystem services beyond pollination, including decomposition, at the country-level [17] and worldwide (bluecarbonlab.org/teacomposition-h2o).

(c) Enhancing food safety, nutrition, and flavour

Citizen science also helps address a third grand challenge in agriculture—the need to improve food safety and nutrition, which overlaps with the SDG goal of increasing health and well-being impacts for consumers. For example, the rise of antimicrobial-resistant (AMR) pathogens is considered by the World Health Organization as one of the greatest threats to global health, including veterinary medicine and agriculture [18]. A recent and ongoing citizen science project enlists the help of the public and farmers to tackle a major challenge for mitigating this threat—figuring out the profile of AMR pathogens in the environment—and has already identified drug-resistant populations of *Salmonella* and Shiga toxin-producing *Escherichia coli* (STEC). Complementing these efforts, several citizen science projects enlist the public to help identify beneficial microbes. For example, citizens send in soil samples from around the globe in an effort to find microorganisms, or microorganism pathways, useful for therapeutics (whatsinyourbackyard.org, drugsfromdirts.org). Such initiatives have already led to the discovery of a novel class of antibiotics [19] and a better understanding of where to look for more in the future [20].

Regarding food safety, citizen science projects can provide information that directly impacts the health of gardeners, farmers, and consumers. For example, researchers partnering with home gardeners have been able to demonstrate that gardens neighbouring mining operations or mine tailings can accumulate considerable levels of arsenic in certain vegetables [21]. The public is being engaged also in studies of how fermented foods like kombucha can help to suppress the growth of human pathogens (aktipislab.org/blog/what-is-kombucha). Citizen science projects are helping gather difficult to access data on real-life risk concerns related to food handling practices within kitchens, such as investigating thermometer use—placement and final endpoint temperatures [22]—as well as information on person-to-person interactions that shed insight on how infectious diseases such as norovirus can move through a population [23].

Unfortunately, citizen science projects dealing with nutrition are rare, if not entirely absent. However, there may be great opportunity for such projects to improve our understanding of how nutrition is affected by how we grow, store, and process food, and how nutrition in turn influences human health. For example, the Royal Society of Chemistry has an educational project where participants evaluate how food preparation and cooking alter the micronutrients (vitamin-C) of their foods using household chemicals (rsc.org/learn-chemistry/resource/res00001280/measuring-vitamin-c-in-food-a-global-experiment?cmpid=CMP00002712). While this project is not citizen science, it could be easily adapted to address specific scientific questions. Similarly, while citizen science projects focusing on the flavours of foods are only beginning to emerge, there are now several ongoing citizen science projects engaging the public in the study of fermented foods. For example, as part of a global Sourdough Project (robdunnlab.com/projects/sourdough), participants are asked to evaluate the smell of their starter, which aids our understanding of the metabolism of the associated microbial communities and provides information about the flavour, nutrition, and shelf life of bread [24]. These types of projects can not only provide insight into the microbial species responsible for the phenotypes of certain foods, but also provide an avenue to address non-normative understandings about microbes [25].

(d) Improving food and food security

Combating global hunger will require innovative basic and applied research approaches directed at improving food security. Citizen science projects contribute to the strengthening of food systems. For example, several citizen science projects are aimed at preserving agricultural biodiversity (agrobiodiversity) through seed exchanges (seedsavers.org/citizen-science-corps) that involve collecting data on variety performance under different environmental conditions and management practices. This approach has been demonstrated as a practical and efficient way for massively evaluating and distributing seeds to strengthen crop diversity and improve seed innovation efforts [26]. Similarly, numerous citizen science projects work with farmers to gather data related to plant breeding (Participatory plant-breeding; PPB) and variety selection (Participatory variety selection; PVS). These efforts increasingly are being paired with the use of emerging technologies to engage the public in crop evaluation through large-scale high-throughput plant phenotyping (phenomics) [27], as well as ground-truthing (calibrating) remotely sensed data [28] that allow researchers to analyse interspecific and intraspecific variation, which would not be possible otherwise [29].

One of the most pressing issues for food security is the need to mitigate and adapt to human-mediated environmental changes, an issue that overlaps with the United Nations Millennium Development Goal of combating climate change and its impacts. Citizen science is contributing substantially to our understanding of the roles of abiotic factors (i.e. climate, soil, water) in agriculture. Regarding climate, there is a long history of public participation—e.g. the foundation of all weather and climate models in the United States have their roots in citizen science efforts that began in the 1800s [30]. These efforts have expanded to include projects aimed at calibrating weather instruments [31], and collecting data on cloud cover (https://vis.globe.gov/clouds), temperature [32], and precipitation [33] to better understand microclimatic variation [34]. Often, these efforts include measuring water and soil health. In fact, citizen science projects now focus on water quality more than any other topic. Developing nations may benefit the most from these efforts, where existing data are scarce and infrastructure to conduct abiotic monitoring may be limited or non-existent.

Farmers, students, and the broader public are also helping to characterize and map soil properties and health at large spatial scales, often at a country or global level, through collection of soil data via mobile apps (e.g. opalexplorenature.org/soilsurvey, globe.gov, ukso.org/mysoil/mysoil.html). The SMAP (Soil Moisture Active Passive) project run by National Aeronautics and Space Administration recruit volunteers to measure soil moisture for the purpose of calibrating satellite instruments. More recently, projects such as eFARM are helping to improve Agricultural Land System (ALS) information through crowdsourcing efforts to obtain land parcel data and household information (using volunteered geographical information) that can be combined with other crowdsourced information from smartphone-based tools along with socio-economic data from surveys and remotely sensed data [35]. Citizen scientists are also helping to measure the impacts that management practices have on environmental health. For example, the use of simple technologies, such as soil kits, is empowering farmers to acquire and practice site-specific nutrient management, resulting in increased yields with reduced fertilizer inputs [36].

(e) Social justice (e.g. gender, race, ethnicity, and equity)

There is a history of citizen science focused on activism and social justice in agriculture, largely through participatory approaches such as community-based participatory research (CBPR) and participatory action research (PAR). For example, CBPR approaches help document the negative health consequences on neighbours of concentrated animal feeding operations (CAFO) and environmental racism resulting from placement of CAFOs [37]. These citizen science efforts, in conjunction with political action, led to policy reforms [38]. CBPR was also used to study environmental contaminants in home gardens, as mentioned above [39].

PAR projects in agriculture are similar to what are described as 'bottom up' [40] or 'co-created' [41] projects in citizen science more generally, where non-research partners actively participate in all aspects of the research, often in an iterative process—research, reflection, and action—with the primary goal to empower participants (stakeholders) and change social practices [42]. Dozens of examples of PAR projects in the field of agriculture address issues from farmer safety and health (exposure to chemicals) [43], to water resource conflict management [44], developing innovative ways to improve animal welfare [45], articulating agrarian (in)justice [46], and understanding how nationality and gender influence assessments for enhancing food security [47]. However, these types of projects may require substantially greater capacity building to deal with political and technical challenges given they are typically more likely to generate politically controversial data [48]. Nevertheless, inviting citizen participation in agricultural research can increase the social impacts and lead to advancements in equality.

(f) Education (achieve universal primary education)

Outreach efforts organized through extension programmes, such as 4-H, Food Corps, Master Gardeners and Junior Master Gardeners in the United States, are helping to connect existing citizen science projects in agriculture to a large network of individuals who often receive credit (volunteer work hours) for their contributions. Such garden-based learning has positive impacts on academic outcomes (particularly science, math, and language arts) as well as social development [49]. Yet, citizen science projects make up only a small fraction of projects in these programmes. Fortunately, there appears to be growing interest among many practitioners in these programmes to incorporate more citizen science.

Several future challenges in agriculture (like those facing society more generally) relate to education. On the one hand, major opportunities exist for linking teaching about agriculture to citizen science as well as farming and gardening [50]. On the other hand, the status quo seems to be in many cases that we are failing in science education, failing to expose children to knowledge about agriculture, and failing to convey the ways in which science and food connect [51]. In this way, connecting citizen science and agriculture in the classroom is greatly needed.

Although historically situated within the domain of Informal Science Education, citizen science has made recent in-roads to the formal science classroom with benefits for teachers, students, and scientists alike [50]. Citizen science programmes have a proven track record of making significant contributions and surprising scientific discoveries [49], demonstrating that students who are engaged in science in which real discovery is possible, will engage with that science more deeply and learn more effectively. Of note, citizen scientists become engaged in data-sorting, analysis, and hypothesis generation [52] and, more generally, in all aspects of the scientific process—exemplified in recent biodiversity projects (bbdata.yourwildlife.org). However, we currently know of only a handful of citizen science farm or garden projects being used in the classroom. One of these projects, the Great Pumpkin Project (http://studentsdiscover.org/lesson/the-great-pumpkin-project/), gets children involved in documenting the pests and pollinators of crops and, in doing so, facilitates learning about food biology (and specifically ecology). A second project, Sourdough for Science (studentsdiscover.org/lesson/sourdough-for-science), challenges students to grow and measure their own sourdough starters as a way to gauge the effect of different flour types on microbial metabolism.

3. Emerging opportunities and challenges at the interface of citizen science and agriculture/food research

(a) Role of technology

In as much as the power of citizen science in agriculture is partially contingent on the ability of scientists to engage multitudes of individuals, this power is also contingent on technology. It is now far easier to connect millions of people digitally; in most countries, cell phone use by farmers is high, often greater than 90% [53]. Several emerging technological innovations in citizen science (and science in general) have the ability to enhance existing citizen science efforts/approaches, create the potential for entirely new ways of engaging the public, but also present new and unique challenges. Artificial Intelligence (AI), drones/sensors, and genetic engineering are emerging technologies that will likely play a major role in revolutionizing agriculture, but they are also becoming increasingly used by the public and in citizen science projects.

Perhaps the most direct way technology will benefit citizen science in agriculture and food research is by converting data into useable information, particularly for those collecting the data. For projects built around identification, a variety of algorithms coupled to camera phones allow plants, and soon pests, pathogens, and pollinators to be identified in the field in near real-time (e.g. iNaturalist.org, [54]). Thus, this technology has the potential to result in greater buy-in, and in turn participation, by making the reward to the participant for contributing more direct and immediate. This may be particularly true when participants are stakeholders. However, the power of AI/machine learning is limited by the quality and quantity of ground-truth data. This presents an ongoing opportunity for citizen scientists to provide data that improve the utility of the technology itself, as with citizen science approaches regarding ground-truthing [55].

Other technologies, such as drones and genetic engineering also present opportunities, but may be more limited in their capacity depending on government regulations. Drones are becoming increasingly accessible to researchers and the public, which means the potential to enlist hobbyists into citizen science projects in agriculture is enormous. A growing number of citizen science projects are already using drones to answer questions in fields outside of agriculture (e.g. citizensciencegis.org) and we speculate it is only a matter of time before they are applied to agricultural systems. Similarly, genetic engineering and gene editing (e.g. CRISPR/Cas9) technologies are becoming cheaper and the public is already using this technology to engineer yeasts to make vegan cheese (realvegancheese.org/#science) and *E. coli* to produce fluorescent proteins (the-odin.com/gene-engineering-kits) in cities across the world, in so-called Do-It-Yourself (DIY) laboratories. However, it is unclear whether and how these technologies will be incorporated into citizen science.

The degree to which drone and genetic engineering technologies are incorporated into citizen science projects in agriculture and food science partly hinges on how regulatory systems adapt to these technologies. In this regard, large, regional projects using an 'air force' of citizen science pilots will require greater coordination than local efforts. Similarly, new genome editing technologies (e.g. CRISPR) make it unclear whether, under some conditions, someone could edit the genes of a plant and legally put it out in their yard or field without a permit. The EPA, USDA, and FDA are all in the process of updating their guidelines under the Coordinated Framework for the Regulation of Biotechnology, and new technologies that could be amenable to citizen science projects are simultaneously challenging regulators to determine what products or processes warrant sufficient risk for formal oversight.

Whether technological innovations create new opportunities for the public to participate in agriculture and food research will depend not only on regulations, but also cost, technical complexity, and preconceptions about the technology. However, cost will likely be the major limiting factor determining whether many technologies are adopted or not. Thus, technologies that are both transformative and cheap are most powerful. For example, handheld sensors are now a reality, but remain expensive. Sharing of open source designs (e.g. PhotosynQ; photosynq.org) and the rise of 3-D printing can hasten the pace these technologies become accessible. Creativity can also make a citizen science approach more tractable. For example, projects that come up with simple, low-cost methods for sampling, such as having participants place socks over their shoes to collect pathogens from the soil [56] or by using existing sensors in smart phones to monitor the environment (e.g. citizenscience.gov/air-sensor-toolbox/#) will allow the public to participate in agricultural research in new and exciting ways.

(b) Opportunity to leverage citizen scientists to support local decision-making

Citizen science is effective in formal settings for engaging students in authentic science learning. By contrast, adult participants may experience fewer learning benefits, because those who self-select into projects can be at the high end of science literacy and conservation behavioural intentions [57]. These highly engaged volunteers, however, may serve to support their communities' science literacy [58] by becoming science communicators themselves. Communication research shows that opinion leaders—knowledgeable, enthusiastic, well-connected community members—are key in promoting not only brands and products but science as well [59]. Participants in citizen science projects are already highly interested in reaching out to other members of their communities [60]; projects can thus serve as ways of identifying and empowering opinion leaders on issues related to agricultural and food systems. Extension already provides powerful examples of the integration of citizen science and science communication in its combination of on-farm research and field day demonstrations. In on-farm research, scientists and farmers collaborate in testing practices in the complex context of an actual farming operation, to determine whether it is robust in the face of the agroecological, social, and economic constraints that farmers experience [61]. Results of on-farm research is often distributed to the community through field days, during which the local community is invited to the test farm for presentations, tours, and opportunities to interact with the research team and especially with the cooperating farmer [62]. Such local knowledge networks are among the most robust methods for promoting improved practices [63].

(c) Challenges in integrating citizen science and extension

Decades of public participation in scientific research have resulted in improved project designs and implementation. However, several challenges remain that are unique to citizen science projects in agriculture and food science or to projects that directly involve stakeholders (e.g. environmental justice and natural resource management). Perhaps most salient are the different data needs and requirements of those participating. Citizen science often relies on borrowed time of participants. Indeed, a major strength of citizen science is that it is generally more cost-effective than traditional approaches due to the cost of labour. For example, in one project, the involvement of farmers or volunteers was estimated to result in 46 and 77% cost reduction, respectively, when compared to private subcontractors [64]. However, these savings depended on the indicators measured and participants involved—volunteers are typically more cost-effective than farmers except in cases where farmer knowledge can inform data collection (e.g. habitat-mapping). Farmers who depend on the food they grow for their livelihood are less likely to have such time and typically are motivated to participate based on their perceptions of whether the results of the project are directly relevant to their livelihood (e.g. improve product yield, build capacity, etc.) [65]; however, see [53]. This contrasts with the motivations of participants in non-agriculture-related citizen science projects primarily made up of nature and science enthusiasts, who are typically motivated by the desire to contribute to scientific research [66], to learn [67], or to be part of a community [68]. Hence, most existing citizen science participants typically are involved in projects related to discovery and human/environmental health.

For every project, it is critical to consider the data/information needs, interests, and concerns of all participants prior to project design and implementation. Generally, the more applied the results (e.g. pest or pathogen surveillance that results in management or policy decisions), the higher the data quality standards and the need for fast turnaround of data into useable information. While data quality and dissemination are also concerns for non-agricultural/food-related citizen science projects, as well as for science broadly, failure to address these concerns will likely have greater economic, human, and environmental consequences and likely affect recruitment and retention of stakeholder (citizen scientist) participation. It is also the case that many agriculture and food citizen science projects will require greater attention to data privacy and ownership concerns. If attention to data privacy and ownership is of concern in a citizen science project, a practical approach is to share ownership of data. There are situations where rules for sharing data within projects and with the public have been established [69]. This may be necessary to ensure the security of sensitive data, accommodate diversity in the observation practices among participants, and protect the privacy of participants.

4. Recommendations for citizen science in agriculture/food research

While there are examples of citizen science projects addressing nearly every grand challenge in agriculture/food science, the absolute number of such projects remains relatively few in comparison to the number of projects that exist in the broader citizen science community. This relative scarcity of agriculture-focused projects is reflected in the largest online portal connecting the public to citizen science projects, where less than 1% of Scistarter's projects (as of 5 April 2018; scistarter.com) contain the tags 'agriculture,' 'food', or 'farm.' Therein lies an opportunity to take advantage of the growing interest in citizen science to build projects focused on food and agriculture. Based on our working group, we have identified several areas where immediate advances seem possible in the near future.

One of the greatest immediate potentials is enhancing connections between citizen science, agriculture, and education. This may be most effectively facilitated by leveraging existing infrastructure in Extension systems or environmental education programmes that support K-12 science teachers. Extension has at least three major strengths to offer. First, Extension programmes provide an opportunity to connect with typically under-represented communities (i.e. those from a different socio-economic background than typically engaged; rural) in citizen science through an organization that has a trusted reputation by these communities [70]. Second, the spatially broad and relatively dense network of knowledgeable professionals (e.g. 4-H agents, agriculture, horticulture, natural resources, family consumer sciences agents, state specialists) provides greater access to diverse places (i.e. farms, feedlots, etc.) as well as people. Third, opportunities exist to design new citizen science projects based on local needs, which are identified through bidirectional exchange of information between stakeholders, either directly or through professional Extension agents and researchers. For example, Extension professionals can act as a bridge from the community to the university by bringing grassroots questions and problems that require research and connecting those questions to research scientists.

While citizen science can benefit from greater connection to Extension programmes it is also true that the need for citizen science projects may be greater and have greater impact in areas that lack extension programmes, such as in countries with emerging and developing economies or regions without intensive agriculture. Citizen science projects are relatively cost-effective [71] and can be designed to promote agricultural sustainability in resource-limited economies. Many parts of the world have similar needs and challenges where citizen science projects could fulfil the role of extension. Given the large geographical scale of the many grand challenges facing agriculture, perhaps the most effective model for maximizing the impact of citizen science projects, while minimizing costs, are multinational projects that include both developing and developed nations, where costs could be spread across institutions and/or governments.

In some ways, the best opportunities may be those that are newer from both citizen science and extension perspectives. Here, we suspect that engagement of urban populations in citizen science about food and agriculture may be a low-hanging fruit. In urban populations, there is both a growing demand by urban farmers for services typically offered through extension [72] and a growing population of urban citizen scientists. We see the diversity of ways projects could engage urban populations is limited only by one's imagination. For example, agritourism is an emerging field. Yet, we know of no citizen science efforts taking advantage of this growing population of people expressly interested in agriculture and food. Similarly, there is a need to provide healthy and fresh food, particularly in tracts that are considered 'food deserts' that are often found in urban areas [73]. Community-based initiatives like community gardens, healthy corner stores, mobile farmers markets, etc. present many opportunities to engage participation in and improve access to healthy foods through citizen science. Further, urban environments are where many pests and pathogens are likely to emerge (e.g. plant pathogens through nurseries [8]). Efforts to identify and control the introduction and spread of pests and pathogens may be best strengthened through citizen science-assisted monitoring and surveillance projects in cities. Last, in cities across the world, communities are organically forming to address scientific questions in DIY laboratories. There is an opportunity to build partnerships with DIY laboratories for researchers at universities or in industry to provide a role similar to extension in helping these communities explore a myriad of topics, from genetic engineering to sustainable agriculture.

Although we provide what we believe are a few low-hanging fruits for building greater capacity for citizen science to address grand challenges in agriculture and food science, there are many topics and issues related to implementing these changes that we do not address. For example: who will lead these efforts? What best practices should be used? How should funding be allocated to aid these efforts? We do not provide specific recommendations to these and other related questions, because there is likely no one-size-fits-all solution or approach. Instead, we believe the best way to answer these questions will come from greater dialogue, through more working groups like we have done here, as well as through ordinary conversations over coffee, lunch, or dinner, conversations that bring together researchers and practitioners with different cultures but similar goals. This may seem like an overly simplistic suggestion. Yet, given how rarely connections between the community of researchers who describe themselves as doing 'citizen science' and those who describe themselves as doing 'extension,' it may be a good first step.

Data accessibility. This article has no additional data.

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