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A Citizen Science-Driven Approach to Food Security in Sub-Saharan Africa

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1. Introduction

Over the last decade, citizen science (CS) projects have increasingly garnered a reputation as an effective tool in scientific research for their efficiency and public engagement. In our recent work, we sought to understand the principles, dynamics, and incentives that allow CS projects to succeed in coordinating decentralized voluntary efforts toward a common objective. This paper builds upon previous work by Fotheringham[1] (2016) and Fotheringham and Jobe (2017).[2] The former conducted a taxonomy of extant CS projects and developed a categorization framework based on the mode through which participants engage in a diverse range of information gathering and analysis exercises; the latter then applied insights gleaned from this study of CS projects to the broader application of crowdsourcing in the digital economy, including the private sphere. These efforts (1) clarified the underlying principles that make CS effective as a mode of decentralized information collection and analysis then (2) considered their applicability beyond public-good activities (i.e., driving scientific knowledge) to the realm of private goods (i.e., value creation in the knowledge economy). Building further on these efforts, this paper seeks to further extrapolate this conceptual framework to a new context in the public sphere: addressing food security and agricultural development challenges facing Sub-Saharan Africa (SSA).

2. Citizen Science

Citizen science (CS) projects, also called 'public participation in scientific research,' have been increasingly touted as a viable model for scientific advancement. For example, CS projects have generated both novel discoveries and vast amounts of useful data in domains as disparate as astronomy, environmental radiation measurement, and ornithology.[3] Indeed, citizen science has been popularized in part because of its ability to generate vast data sets that would be otherwise be too costly, time consuming, or geographically diverse to obtain.[4]

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[1] Fotheringham, "Survey Citizen Science Initiatives: Toward a Participant-Focussed Conceptual Framework."
[2] Fotheringham and Jobe, "Citizen Science in The Digital Age: Connecting 'Unapplied Capacities' With 'Unmet Needs.'
[3] Shuttleworth Foundation, "About – Safecast"; Wright et al., "Understanding the Motivations and Satisfactions of Volunteers To Improve The Effectiveness Of Citizen Science Programs."
[4] Turrini et al., "The Threefold Potential of Environmental Citizen Science - Generating Knowledge, Creating Learning Opportunities and Enabling Civic Participation."

Beyond their immediate utility in advancing scientific knowledge, CS projects have also demonstrated the potential to increase scientific literacy and produce positive attitudinal changes towards scientific research and learning among their participants.[5] In the domain of ecology and conservation, CS projects have been identified as a means of increasing public participation and policy-making effectiveness.[6] However, CS faces its challenges. While citizen science (CS) projects have been demonstrated to produce accurate (typically open access) data, only a small proportion of these data make their way to publication in a scientific journal.[7]

The majority of extant literature on CS projects themselves tends to focus on characteristic aspects such as the reliability of data they produce, their advantages over conventional research project structures, and their effects on participants' attitudes and scientific literacy.[8] In contrast, our previous work has examined the various functions of participants within CS projects in order to develop an approach to understanding how crowdsourcing and participatory research—given the ubiquity of ICT in the digital age—may be applied beyond the domains of scientific research and conservation efforts.

2.1 *Citizen Science in the Digital Economy and Beyond*

CS in its current form would not exist without the widespread adoption of smartphones and Web 2.0 platforms, which have enabled instant and ongoing global interconnectedness.[9] Although CS is characterized by unique forms of participation and interaction, it can be understood more broadly in terms that apply equally to similar non-CS activities such as end-user innovation, mass collaboration, and crowdsourcing.[10] In a fundamental sense, we consider all such activities to be means of connecting 'unmet needs' with 'unapplied capacities'. In the digital economy, this connection is maintained on an ongoing basis, in real time, and across an interconnected globe. Further, connections need not operate unidirectionally in discrete phases from 'needs' to 'capacities' or vice versa; they often operate bidirectionally and on a continual basis.

The Zooniverse platform is a ready example of such connections within the CS space. Through the platform, volunteer participants are able to seek out exciting initiatives to which they can apply their capacities, whether they are highly skilled or simply willing to carry out tasks requiring a human eye or

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5 Crall et al., "The Impacts of an Invasive Species Citizen Science Training Program on Participant Attitudes, Behavior, And Science Literacy."
6 Tulloch et al., "Realizing the Full Potential of Citizen Science Monitoring Programs."
7 Theobald et al., "Global Change and Local Solutions."
8 Turrini et al., "The Threefold Potential of Environmental Citizen Science - Generating Knowledge, Creating Learning Opportunities and Enabling Civic Participation."
9 McKinsey Global Institute, "Disruptive Technologies: Advances That Will Transform Life, Business, and the Global Economy."
10 Thomke and von Hippel, "Customers as Innovators."

basic decision-making abilities in service of the public good. At the same time, researchers, conservationists, or users with raw, unanalyzed datasets can use the Zooniverse platform to find and connect with willing participants.

CS projects find additional benefits not often present in more traditional research and data-gathering domains. Such benefits include an increased number and geographic distribution of available participants, reduced transaction and labour costs, and an increased public interest in the subject area.[11] However, our previous work[12] (2017) revealed that these strengths may not apply to economic value-creation activities that serve a profit motive, potentially for the same reasons not much CS work gets published. This points to the fact that, while CS is a promising tool for collecting data and translating it into knowledge, it can be difficult to find a place for this knowledge (i.e., both in terms of dissemination and eventual use-cases).

Since the beginnings of organized citizen science over a century ago, the vast majority of CS projects have focused on conservation and ecological research.[13] Yet the advantages of participatory research—scalability, cost-effectiveness, and public engagement among them—may translate into other fields of research such as agriculture and agricultural development.[14] Indeed, CS projects—as part of a broader trend within the international scientific community towards open data and crowdsourcing—have been identified as holding significant potential to address many of the most difficult challenges in agricultural development today.[15]

2.2 *Why Sub-Saharan Africa as a Case Study?*

Our reasons for choosing SSA as a case study are threefold. First is the utilitarian case: where traditional efforts have largely failed, CS-inspired projects offer many promising pathways to address severe global challenges in poverty and food insecurity. Globalization has had a disproportionate effect within the developing world due to a wide variance in relative institutional and economic capacities held between various regions and countries.[16] SSA has suffered the largest failure of globalization in terms of poverty reduction and pro-poor growth. In the period between 1981 and 2005, the proportion of people in

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[11] Crall et al., "The Impacts of an Invasive Species Citizen Science Training Program on Participant Attitudes, Behavior, And Science Literacy."
[12] Fotheringham and Jobe, "Citizen Science in the Digital Age: Connecting 'Unapplied Capacities' With 'Unmet Needs.'"
[13] Crall et al., "The Impacts of an Invasive Species Citizen Science Training Program on Participant Attitudes, Behavior, And Science Literacy."
[14] Ryan et al., "The Role of Citizen Science in Addressing Grand Challenges in Food and Agriculture Research."
[15] Ryan et al.
[16] Thorbecke, "The Interrelationship Linking Growth, Inequality and Poverty in Sub-Saharan Africa."

SSA living under 1.25 USD per day virtually remained constant while “the absolute number of poor almost doubled.”[17] Indeed, rates of poverty and hunger in SSA have been climbing since 2015.[18]

Second, CS-driven projects may be particularly well-suited to overcoming challenges that are, while not endemic to SSA, particularly common there. The vast majority of the labour force in sub-Saharan countries participates in the agriculture sector by utilizing traditional farming practices and producing entirely for personal consumption within a family unit.[19] Additionally, a lack of infrastructure such as irrigation means that the widespread adoption of improved crop varieties and modern agricultural inputs, even those which have been subsidized to promote development, is unlikely.[20] The CS approach requires less government coordination and physical infrastructure than traditional research approaches. In short, the CS approach may be able to circumvent barriers that face orthodox development approaches and fulfil these unmet needs.

Our third reason is the extent to which the capacities necessary for the implementation of CS-driven projects already exist in SSA. While government coordination and physical infrastructure may be lacking, CS projects have the potential to make use of existing local infrastructure, local knowledge, and other capacities. These include but are not limited to satellite imagery of land cover, local ethno agronomic knowledge, widespread mobile phone adoption, and existing development networks.[21] In sum, there are unique demands and unique capacities that, together, make SSA a good case study for the application of CS projects and CS framework to the food security and sustainable agricultural development context.

While these features make SSA a particularly suitable early case, we must note that other regions and development contexts and challenges may offer promising directions for future work. Indeed, some of the projects highlighted here have been carried out concurrently in South Asia and Central America.[22] Nonetheless, SSA provides clear-cut examples of the benefits of the CS-approach.

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[17] Thorbecke.
[18] FAO, “2019 - The State of Food Security and Nutrition in the World (SOFI): Safeguarding Against Economic Slowdowns and Downturns | World Food Programme.”
[19] Lemba et al., “Intervention Designs for Household Food Security.”
[20] van Etten, “Crowdsourcing Crop Improvement in Sub-Saharan Africa.”
[21] Rist and Dahdouh-Guebas, “Ethnosciences—A Step Towards the Integration of Scientific and Indigenous Forms of Knowledge in The Management of Natural Resources for the Future”; Ramirez-Garcia, “Ethnoagronomy And Sustainable Community Development”; Fritz et al., “Geo-Wiki”; See et al., “Improved Global Cropland Data as an Essential Ingredient For Food Security.”
[22] van Etten et al., “First Experiences with a Novel Farmer Citizen Science Approach.”

2.3 Food Security in SSA

Food security has been defined by the Food and Agriculture Organization of the United Nations (FAO) in the following terms, "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."[23] Since 2015, global food insecurity and hunger have increased in both relative and absolute terms.[24] In sub-Saharan Africa (SSA), undernourishment has increased to 22.8 per cent—the highest proportion of any subregion today[25].

Through a preliminary examination of relevant publications, it appears there are at least four specific dimensions of food security in SSA which are being addressed by existing and potential CS- or crowdsourcing-based projects. The first of these dimensions is seed development and innovation, which has been addressed by community seed banks, participatory variety selection projects, and participatory plant-breeding projects[26]. A second dimension, environmental and crop data collection and analysis, includes land use and land cover data projects, water and rainfall observations, soil conditions, pest observations, and crop disease observations.[27] Thirdly, human mobility data has been identified as a means to predict human responses to famine and ecological disasters.[28]

The last area of food security for which the CS approach holds promise is improving data collection on inventory rotation, tracking foodborne illness, and monitoring disease and malnutrition.[29] Although CS projects addressing this dimension of food security are undoubtedly important, we consider them to fall beyond the scope of this paper as they do not directly pertain to agricultural development.

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23 FAO, "Rome Declaration and Plan of Action."
24 FAO, "2019 - The State of Food Security and Nutrition in the World (SOFI): Safeguarding Against Economic Slowdowns and Downturns | World Food Programme."
25 FAO.
26 van Etten et al., "First Experiences with a Novel Farmer Citizen Science Approach"; van Etten, "Crowdsourcing Crop Improvement in Sub-Saharan Africa."
27 See et al., "Improved Global Cropland Data as an Essential Ingredient for Food Security"; Fritz et al., "Geo-Wiki"; Rossiter et al., "Can Citizen Science Assist Digital Soil Mapping?"; Ramcharan et al., "A Mobile-Based Deep Learning Model for Cassava Disease Diagnosis."
28 Zufiria et al., "Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security."
29 Soon and Saguy, "Crowdsourcing"; Enenkel et al., "Food Security Monitoring via Mobile Data Collection and Remote Sensing."

3. Conceptual Framework and Methodological Limitations

This account is preliminary—both as it relates to the literature and in terms of the available evidence for emergent trends and possibilities. Our aim is merely to advance clear argumentation demonstrating the possibility—if not probability—of a range of diverse outcomes and their implications. This will be achieved first through bringing greater conceptual clarity to differentiated modes of CS participation, and second through illustrative examples corresponding to each category, appearing, respectively, in the Conceptual Framework and Analysis sections to follow. The case studies presented in the Analysis section are intended only to provide reference points for recent and emerging developments in CS-based food security projects in SSA.

3.1 Conceptual Framework

Our previous work[30] sought to categorize CS projects based on the function of CS participants within the project. Rather than pre-establishing these categories and then populating them with examples, this study examined approximately 30 different CS projects and inductively created categories to highlight such distinctions. The CS projects surveyed were sufficiently different to establish four categories: Active Data Collection, Passive Data Collection, Skilled Data Analysis, and Unskilled Data Analysis. This section provides a brief outline of each category.

3.2 Active Data Collection

As the name suggests, participants in Active Data Collection projects play an active role in collecting data to be used in the study. These projects usually require participants to have some knowledge of the field they are working in, and generally provide them with this information as a part of the project. Participants do not analyze the data but submit it (often electronically) to the researchers. In this model, ‘participatory monitoring’ projects, such as migratory bird counts and volunteer water sampling programs, are included in this category. Likewise, participatory variety selection projects and soil mapping projects are included in this category.

3.3 Passive Data Collection

Participants in Passive Data Collection projects do not make regular, pointed efforts to collect data, but rather consent to using some kind of sensor to monitor some aspect of their environment. These types of projects are sometimes considered to be distinct from Citizen Science because they often do not actively involve their participants. In the context of SSA food security projects, this category similarly

[30] Fotheringham and Jobe, “Citizen Science in the Digital Age: Connecting ‘Unapplied Capacities’ With ‘Unmet Needs.’”

includes data gathered in some way by people who could only passively be characterized as 'participants,' such as data collected from mobile phone users.

3.4 Skilled Data Analysis

Participants in Skilled Data Analysis projects analyze data provided to them by the research organization running the project. These projects require a substantive degree of relevant knowledge in order to contribute. Some Skilled Data Analysis projects provide participants with training modules in order to gain this knowledge, while others require that participants pass a test of their knowledge in order to participate. Both of these measures are intended to ensure that participants' contributions are accurate.

3.5 Unskilled Data Analysis

Participants in Unskilled Data Analysis projects do not require more than a layperson's knowledge of the data they are analyzing. For instance, such analysis can be the identification of simple colours or objects in photographs, or the transcription of handwritten documents. These projects often require analyses to be verified by multiple participants to ensure accuracy.

Table 1: Characteristics of CS Projects by Category

Category	**Participants collect data**	**Participants analyze data**	**Researchers collect data about participants**	**Requisite level of knowledge for participation**
A.D.C.	Yes	No	No	Sometimes
P.D.C.	Yes	No	No	Sometimes
S.D.A.	No	Yes	Sometimes	Yes
U.D.A.	No	Yes	Sometimes	No

4. Case Studies & Analysis

This section examines if and to what extent each category of the conceptual framework applies to various modes of participation in crowdsourced or CS-like projects in the context of food security in SSA. It is our aim that, with features of specific CS projects in mind, analogies and disanalogies with existing and prospective crowdsourcing food security and development projects will become more readily apparent. After establishing these benchmarks for comparison, we proceed to describe and compare existing corollaries in SSA food security and explore the potential for corollaries that have not yet been established.

This section examines specific participatory research or crowdsourced projects from the SSA context. While there are compelling examples that align with three of the categories in our previous typology, these examples reflect the emergent and exploratory nature of CS and similar projects within the space of agricultural development and food security, especially in SSA. Two of the examples presented here are INGO-funded pilot research programs concerned with agricultural development and food security.[31] Though the experimental nature of these projects reflects the infancy of participatory and crowdsourcing-based research in addressing food insecurity and agricultural development in SSA (and elsewhere), we agree with the associated researchers that, together, these projects demonstrate considerable promise and point to several potential policy avenues.

4.1 Active Data Collection: TRICOT Projects

The Triadic Comparison of Technologies (Tricot), part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCFAIS)[32], is an approach to participatory variety selection (PVS) that incorporates elements of informal research and design (IRD). However, this approach also represents a novel development in PVS in four respects: (1) the variety selection is conducted through single-blind trials; (2) the data are preferably reported by farmers themselves; (3) data analysis is conducted through the Bradley-Terry model for ranking data; and (4) the trial data is assessed alongside relevant environmental data. This project was developed as a contribution to the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS). Its constituent teams conducted pilot variety selection trials in India, Kenya, Tanzania, Ethiopia, Honduras, Guatemala, and Nicaragua.

The basic design of a tricot variety trial involves the distribution of three unnamed seed varieties in separate packets to each participating farmer. Participants then grow these varieties in trial plots

[31] van Etten et al., "First Experiences with a Novel Farmer Citizen Science Approach"; Fritz et al., "Geo-Wiki."
[32] van Etten et al., "First Experiences with a Novel Farmer Citizen Science Approach."

alongside their own varieties. At the end of the crop cycle, participants rank order the performance of each trial variety with respect to "plant vigour, pest resistance, disease resistance and plant architecture" as well as overall performance relative to their own local variety. These pilot projects, conducted to develop and evaluate the methodology and potential of the tricot approach, yielded results indicating that the tricot method of participatory variety selection can effectively generate useful variety performance data for both seed and input suppliers, along with participating farmers themselves. This is particularly notable given that participation in a tricot PVS project is suitable for those who possess low levels of literacy.

The tricot pilot projects are an excellent example of an Active Data Collection project. Through the involvement of non-expert (e.g., non-agronomist) smallholder farmers with potentially low levels of literacy, tricot projects are capable of producing useful and reliable data on a massive scale. In particular, van Etten et al. identify three particular features of the tricot approach that make it useful and scalable: "low skills requirement"; "automatization and elimination of tasks"; and "cost reduction." These results are consistent with our previous finding that Active Data Collection projects are particularly well-suited for ecological projects because they offer a highly efficient means to obtain the necessary geographic breadth of data for the research in question.

While van Etten et al. also identify the need for further methodological development of the tricot approach, it nonetheless represents a promising avenue for smallholder participation in variety selection and agricultural innovation generally. As such, van Etten et al. call for the application of the tricot approach to be expanded beyond PVS into other farm technologies such as fertilizers and crop management products.

4.2 Passive Data Collection: Seasonal Mobility Profiles

The project "Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security"[33] brought together a team of researchers from public research institutions, including the United Nations World Food Program Senegal and various European universities, to analyze anonymized and aggregated mobile phone data from a Senegalese telecommunications network. Using the supplied data sets, the team was able to identify delimited "livelihood zones" and track population variance within and among these zones over the course of a year (the temporal scope of the data set used). By combining these observations, the team could identify

[33] Zufiria et al., "Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security."

specific mobility patterns (or "Matrix of Individual Trajectories" (IT-Matrix)) among large groups of people to produce "distinct human mobility profiles."

While this project centres on developing new methods and applications for the analysis of mobile phone data, the data itself (human mobility data) are collected passively through the regular use and carrying of mobile phones. As with so many other developments in both CS and big data, these data sets are relatively novel and would not exist without widespread adoption of smartphones throughout SSA (in this case, Senegal). Though this project is not a CS project in the sense that the individuals whose mobile phone data was aggregated were not active participants, we for Passive Data Collection projects under our framework.

Zufiria et al. advance this method of analyzing mobile phone data as a means of obtaining quantitative data on human behaviours related to agricultural cycles. This model presents a potential means by which policymakers in SSA could predict human mobility responses to external shocks such as disease outbreaks and food shortages.

In our previous research[34] examined this category through a project called "Safecast." This project provided participants with open-source designs for sensor modules used to measure environmental radiation and other air pollutants in their own homes. Using these data, Safecast "maintains the largest open dataset of background radiation measurements ever collected" with over 50 million readings to date.[35] Similar dedicated sensors, though relatively inexpensive, are not likely to be a viable means of passive data collection in many countries within SSA given current levels of poverty.[36] The project conducted by Zufiria et al. provides further evidence that the existing prevalence of mobile phones may be a useful alternative route for the passive collection of data.[37]

4.3 Skilled Data Analysis: NULL

When examining existing food security and agricultural development projects in SSA, we were unable to find projects which fit the criteria of this category. Although we found many projects, such as the Passive Data Collection project above, which involved skilled data analysis on the part of geographically diverse participants, these participants were too few in number and too specialized in the

[34] Fotheringham and Jobe, "Citizen Science in the Digital Age: Connecting 'Unapplied Capacities' With 'Unmet Needs.'"
[35] Shuttleworth Foundation, "About – Safecast."
[36] van Etten et al., "First Experiences with a Novel Farmer Citizen Science Approach."
[37] Zufiria et al., "Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security."

field to reasonably be regarded as "citizen scientists," or indeed, "crowds."[38] While these projects often produce novel, data analysis-based solutions to food security and agricultural development issues, they do not offer the same benefits of scalability afforded by CS and crowdsourcing projects.[39]

As outlined in the previous section, our previous study[40] found that only 11 of the 145 CS projects studied could be classified as Skilled Data Analysis projects. More than half of these projects studied astronomy, and many of them relied upon participants' preexisting knowledge. While there are many amateur astronomists for instance, we suspect that very little unapplied capacity (in the form of unpaid skilled amateurs) exists to provide skilled data analysis that would advance food security and agricultural development efforts in SSA. It is also possible that the kinds of skilled data analysis currently required for advancing these efforts are not suitable for non-expert participants generally.

The case study used for Skilled Data Analysis in our previous work, Agent Exoplanet, is operated by the Los Cumbres Observatory Global Telescope Network. As a part of the project, citizen scientists are trained to use online software to detect the presence of exoplanets, and to analyze and classify 'lightcurves,' which allows researchers to estimate the size, orbital direction, velocity, and atmospheric composition of the exoplanets. While a similar format may be adopted for image-based disease detection, for instance, our preliminary findings suggest that these types of projects are less common both in the CS space and in comparable food security and development projects.

4.4 Unskilled Data Analysis: GEO-Wiki Project

GEO-Wiki is an online Web 2.0 platform designed to combine Google Earth satellite imagery and functionality with a crowdsourcing platform in order to improve global land cover data and to create hybrid land cover products which afford improved accuracy.[41] Using GEO-Wiki as a platform, USAID created a project wherein participants analyzed landsat imagery in Ethiopia in order to create an improved land cover product for Ethiopian crop land. Participants analyzed 1km^2 sections of land imagery—with about five per cent of Ethiopia's total land mass being analyzed. Through a process of interpolation, this sample was then used to create a cropland map for the whole country.[42]

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38 Pokhriyal and Jacques, "Combining Disparate Data Sources for Improved Poverty Prediction and Mapping"; Ramcharan et al., "A Mobile-Based Deep Learning Model for Cassava Disease Diagnosis."
39 Turrini et al., "The Threefold Potential of Environmental Citizen Science - Generating Knowledge, Creating Learning Opportunities and Enabling Civic Participation."
40 Fotheringham and Jobe, "Citizen Science in the Digital Age: Connecting 'Unapplied Capacities' With 'Unmet Needs.'"
41 Fritz et al., "Geo-Wiki."
42 See et al., "Improved Global Cropland Data as An Essential Ingredient for Food Security."

Through a ground-truthing study, the land cover maps created through the project were shown to be more accurate than any existing land cover products for Ethiopia.[43] This individual project demonstrates the potential for the citizen science approach—and the use of GEO-Wiki in particular—to improve land cover data throughout SSA, where many countries would benefit from more accurate and comprehensive land cover products.

In our previous work[44], we identified Old Weather as a particularly fitting example of an Unskilled Data Analysis project. Old Weather, which is offered through the cooperation of multiple museums and archives, is a project in which participants transcribe handwritten text from digital images of ship logs from the 19th and 20th centuries and collect relevant information on weather and sea ice conditions observed and recorded by the ships' crews. This meteorological data is then used to improve the accuracy of reanalysis and simulations of climate data. Although Old Weather and GEO-Wiki are substantially different projects in both form and content, both projects utilize the ability of generally un-skilled participants to analyze vast amounts of data that are simultaneously readily available and, prior to being analyzed, difficult to make use of.

5. Discussion & Policy Implications

This section is intended as a preliminary step toward applying a CS framework for voluntary and broad-based participatory research to the context of food security and agricultural development efforts in SSA. As such, all of the policy ideas presented here are similarly preliminary and high-level and address neither specific challenges and policy concerns nor detailed pathways for their implementation. Nevertheless, our hope is that the following could inform further study and policy discussion.

Given the existing literature and food security projects which are already underway, it is possible that CS-based approaches are a feasible direction for international development—particularly sustainable agricultural development—in the context of SSA. While globalization has ameliorated poverty, hunger, and food insecurity for many, it has not been overly effective in reducing absolute levels of poverty.[45] In many ways, SSA and other developing regions have been excluded from the benefits of globalization, partly due to a low prioritization of pro-poor development strategies.[46]

43 See et al.
44 Fotheringham and Jobe, "Citizen Science in the Digital Age: Connecting 'Unapplied Capacities' With 'Unmet Needs.'"
45 Wade, "Is Globalization Reducing Poverty and Inequality?"
46 Nissanke, "A Quest for Pro-Poor Globalization"; Nissanke and Thorbecke, "Channels and Policy Debate in the Globalization–Inequality–Poverty Nexus."

For many of the same reasons globalization garners criticism, critics also have reason to be skeptical of development approaches that offer technology as a panacea for the endemic and seemingly intractable challenges—such as poverty traps of foreign aid and natural resource extraction[47]—that face most countries in SSA. Like globalization, groundbreaking advancements in biotechnology have largely fallen short on their promise to all but eradicate food insecurity, notwithstanding modest and uneven benefits to the developing world.[48] As these pitfalls make clear, the right institutional features must be in place to ensure that technology-driven development opportunities (e.g., access to mobile phones) truly help improve food security outcomes through the provision of public goods.

A CS-based approach may offer more effective solutions to regional food security and development challenges than these traditional approaches. By contrast, CS-driven initiatives (ongoing and prospective) largely operate outside of profit-motive incentives. Instead, they present the opportunity to marshall international development money funds, along with resources from corporate social responsibility efforts, to provide tools that will help (a) smallholder subsistence farmers and (b) government policymakers seeking to advance the public good. Indeed, one positive feature of CS-inspired approaches is that they have the potential to exist independent of the forces of economic globalization often rightly criticized for failing to achieve their purported benefits vis-à-vis poverty, food security, and agricultural development in SSA.

Moreover, the CS-driven approach to agricultural development and food security is realistic about what opportunities exist given the technology and available to most countries in SSA; while mobile phone adoption is prevalent, the farm machinery and infrastructure (e.g., irrigation) necessary for precision agriculture remain mostly out of reach. How can the mass adoption of cell phones and Web 2.0 be used to improve food security and development? It would appear that many potential answers to this question exist in the realm of CS and related approaches, which have been elucidated in our previous work (and that of others).[49] Much as how, in the commercial context, the vast collective populations of SSA countries can constitute a viable market despite low buying power, large populations can also constitute a large base of voluntary inputs into knowledge creation activities and processes in the CS context.[50]

Nevertheless, there are still significant challenges associated with large populations facing poverty and low levels of education. Thankfully, high levels of education are not a prerequisite for

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[47] Thorbecke, "The Interrelationship Linking Growth, Inequality and Poverty in Sub-Saharan Africa"; Perry et al., "Poverty Reduction and Growth."
[48] Taylor and Cayford, "American Patent Policy, Biotechnology, and African Agriculture."
[49] Ryan et al., "The Role of Citizen Science in Addressing Grand Challenges in Food and Agriculture Research"; Soon and Saguy, "Crowdsourcing"; See et al., "Improved Global Cropland Data as an Essential Ingredient for Food Security."
[50] Diamandis and Kotler, "Abundance."

many—perhaps even most—modes of participation, particularly Passive Data Collection and Unskilled Data Analysis. Even the tricot approach (Active Data Collection), which does rely on the agricultural knowledge and practices of rural smallholder farms, does not exclude those with low levels of literacy from participation.[51] Ultimately, this section presents policy discussion that applies insights drawn from Section 3 case studies; all recommendations relate to and cut across all four categories of the framework.

5.1 Pathways to Policy Impact

Setting the iterative process of developing more CS-based projects in motion will require significant government efforts, both foreign (e.g., aid and expertise), and domestic (e.g., policy implementation and oversight). Considerable support will be required, primarily for coordination, but also potentially to incentivize continual participation of 'citizens' whose engagement may wane over time.[52] However, using policy to build up the institutional and infrastructural (e.g., technological) capacity to better leverage technology toward achieving food security goals represents a promising pathway for international aid dollars. This is especially true given the extent to which most past efforts conducted through orthodox approaches to development have failed.

CS initiatives, especially in the context of sustainable development and food security, are generally not profit-driven. Instead, they exist to provide and enrich public goods such as ecological conservation, public health, and general advancement of the knowledge frontier. Goods that are both non-rivalrous and nonexcludable will be undersupplied in the free market, and thus can only be supplied at socially optimal levels by the public sector.[53] Indeed, dimensions of food security that are currently addressed by CS-driven projects such as non-improved crop variety selection and land cover products tend to be associated with low commercial exploitability, and to this extent, may be unlikely to attract much interest from the private sector. This is not to say that these efforts are necessarily opposed to commercial development; in broad terms, they can perhaps best be characterized as existing alongside them similar to open software and commercialized software, to borrow an example from van Etten.[54]

5.2 Linking & Coordinating Existing Efforts

Just as with other development contexts, the food security and agricultural development space is composed of many disparate actors, including NGOs, INGOs, governments, international governmental

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[51] van Etten et al., "First Experiences with a Novel Farmer Citizen Science Approach."
[52] van Etten, "Crowdsourcing Crop Improvement in Sub-Saharan Africa"; Rossiter et al., "Can Citizen Science Assist Digital Soil Mapping?"; Wright et al., "Understanding the Motivations and Satisfactions of Volunteers to Improve the Effectiveness of Citizen Science Programs"; Crall et al., "The Impacts of an Invasive Species Citizen Science Training Program on Participant Attitudes, Behavior, And Science Literacy."
[53] Varian, *Microeconomic Analysis*.
[54] van Etten, "Crowdsourcing Crop Improvement in Sub-Saharan Africa."

organizations like the FAO, global epistemic communities, and private technological and agricultural companies. Notable organizations dedicated to researching and improving food security and sustainable agricultural development in SSA (among other regions) include the Open Ag Data Alliance, Group on Earth Observations (GEO), and Global Partnership for Sustainable Development Data. Many of these organizations have directly funded or helped to coordinate the projects featured in this paper.

However, the CS-based approach requires iterative and gradually more coordinated efforts—newer iterations of existing projects can tweak design, implementation, and objectives to better align with those of other adjacent projects—all in the context of coordinated, mutually-beneficial larger scale food security efforts. For example, as outlined in Enenkel et al.'s study of a Doctors Without Borders (MSF) mobile phone-based food security project in Central African Republic, there is a great deal of potential for this kind of alignment to yield further efficiencies. Enenkel highlights that "creating internal capacities within aid organizations is...not enough, because large data volumes and tailored products require dedicated hardware and expertise," thus necessitating "partnerships between the research community and stakeholders who can apply these solutions in the field."[55] Such a partnership might take the form of 'stacking' food security data collection with vaccination campaigns, or the distribution of tricot trial seed packets from existing aid distribution points.[56] Leveraging existing capacities in this way will likely be crucial to the success of a broad-based CS approach to food security and development.

In another example, (Blank et al.) points out that most barriers to improving global cropland data relate not to technology but rather "the need to harmonize the definition of cropland, share existing data more openly and target future mapping efforts in areas where this information is currently lacking." Similarly, See et al.[57] point to a host of coordinated initiatives to promote greater data sharing and open data access as evidence of greater coordination that will likely bring many benefits in that "the sharing and integration of data is an inexpensive yet effective solution."[58] One particularly relevant example is a project between the UN and the European Space Agency that provides "a variety of crop and land use maps" to SSA countries including Botswana, Niger, and Gambia.[59]

5.3 From Human-Driven to Automated

Fostering greater interconnection between existing CS-based approaches is also a likely precondition to eventually applying more sophisticated technologies to powerful use cases that could

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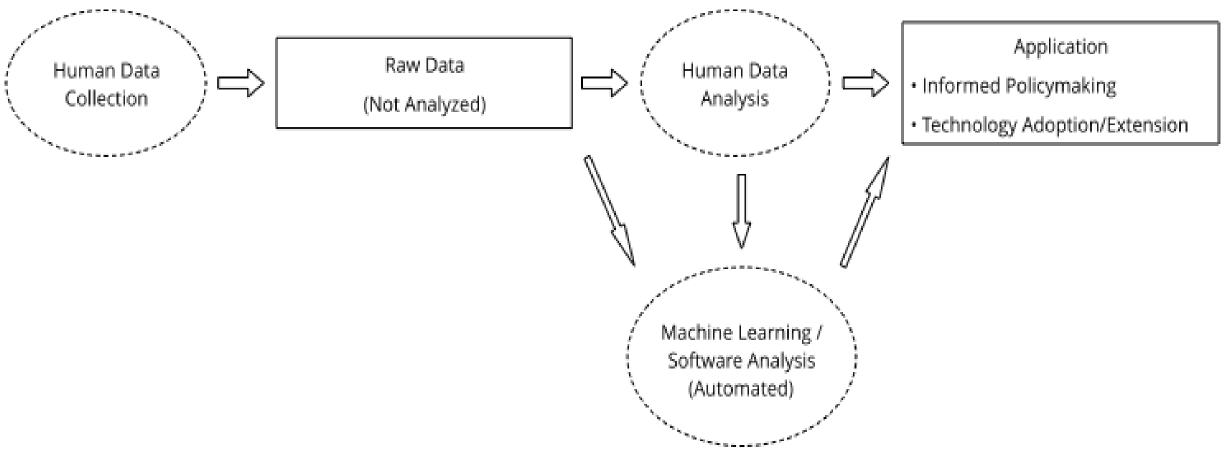
55 Enenkel et al., "Food Security Monitoring via Mobile Data Collection and Remote Sensing."
56 Enenkel et al.; van Etten, "Crowdsourcing Crop Improvement in Sub-Saharan Africa."
57 See et al., "Improved Global Cropland Data as An Essential Ingredient for Food Security."
58 See et al.
59 See et al.

greatly scale food security efforts in SSA. While initial findings and analysis from CS-driven projects are useful in their own right, longer-term strategies should seek to move towards a more efficient (and thus scalable) form if this path for international development is to succeed on a large, transformative scale. For instance, the human data analysis performed in many CS projects (GEO-Wiki and Old Weather are two examples of Unskilled Data Analysis highlighted here) is a precondition for machine learning, which is both cheaper and more scalable. Alongside added incentives that may increase or maintain the supply of human participants for these products, machine learning may well allow software to address any shortage of participants and further increase efficiency of research.

Figure 2: [Facilitating Efficiencies Through Machine Learning]



In this sense, both skilled and unskilled data analysis projects may yield training sets for machine learning in addition to the desired data from the project itself. One existing example in food security and agricultural development in SSA is a computer program which can recognize cassava diseases in digital images with an accuracy as high as 93 per cent through the use of these training sets. For this program to be applied in the field, these photos could be captured with remote sensors or with mobile phones.[60]

Indeed, similar data sets exist for many human Skilled and Unskilled Data Analysis projects which are presumably waiting to be used as training sets that could ultimately serve to automate the same analysis processes altogether.[61] This is illustrated in Figure 2, wherein data sets produced by human data analysis are shared for use as training sets in machine learning applications. This open transfer of data could facilitate automation of human analysis, which in turn would free up human capital (in the form of citizen scientists) for participation in other projects.

[60] Ramcharan et al., "A Mobile-Based Deep Learning Model for Cassava Disease Diagnosis."
[61] Ramcharan et al.; Ryan et al., "The Role of Citizen Science in Addressing Grand Challenges in Food and Agriculture Research."

5.4 Making Results Actionable

Perhaps the most critical component of a CS-inspired approach to agricultural development and improving food security outcomes is the translation of new data into actionable knowledge and insights. To this end, the most important objective is putting this information and knowledge in the hands of smallholder farmers (far beyond the scope of those who typically participate directly in CS or CS-inspired projects). While there are likely several ‘easy wins’ for many smallholder farmers in terms of adopting better-informed practices, the greater challenge is how to reach and influence this majority. While the project of Van Etten (2011) offers a compelling approach to involving more farmers themselves in seed innovation and distribution through technology, the next step is developing strategies to scale such participatory benefits to a larger participant base.

Another aspect of this challenge is that much CS-derived information is more applicable to policy decision-making vis-a-vis food security than to the decisions facing individual smallholder farmers. For instance, understanding large-scale land use and potential human mobility responses to external shocks (e.g. droughts and food shortages) would undoubtedly help policymakers anticipate and better respond to major food security disruptions.[62]

Moreover, CS-driven data collection projects are capable of supplementing existing qualitative information (e.g. known regions with intensive cultivation or human mobility patterns) with reliable quantitative data. In these examples, this data has been derived from existing sources such as landsat imagery and anonymized mobile phone data. The function of these projects was to make these existing data sets usable for informing public policy through human analysis. Indeed, based on the results of their project Zufiria et al. (2018),[63] concludes that, “under strict and secure privacy frameworks, the aggregated analysis of populations’ mobility could be a valuable tool to help policy makers and practitioners quantify and uncover new population movement phenomena” in order to design “better policies and social protection programs.”

Last, in the case of seed selection and innovation, it is important to note that policymakers must consider the implications vis-a-vis intellectual property rights (IPR) when disseminating CS-derived information to influence the seed selection behaviour of smallholder farmers. Though “smallholder farmers are not substantial participants in formal seed markets, which are characterized by among others

[62] See et al., “Improved Global Cropland Data as an Essential Ingredient for Food Security”; Zufiria et al., “Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security.”
[63] Zufiria et al., “Identifying Seasonal Mobility Profiles from Anonymized and Aggregated Mobile Phone Data. Application in Food Security.”

certified seeds or seeds protected with some form of IPR,"[64] there has been a complicating trend of international treaties bringing Indigenous seed varieties under the scope of IPR. Nonetheless, CS-driven projects have the potential to promote informed policymaking in the food security context through the mass collection, analysis, and dissemination of relevant data.

6. Conclusion

Building further on the CS categorization framework of Fotheringham 2016 and its application beyond the strict realm of CS (Fotheringham & Jobe 2017), this paper examined some of the current and potential implementations of CS-driven approaches to food security and agricultural development in SSA. While their design and implementation remain in the preliminary stages, there is encouraging evidence that CS-based projects may have the potential to overcome many of the barriers faced by orthodox agricultural development approaches. In particular, CS-based projects hold the potential for mass data collection and analysis conducted by volunteer participants, which in turn serves to lower costs and improve efficiency of data-driven development efforts. Additionally, a CS-driven approach stands to capitalize on existing capacities; in the context of SSA, these capacities include local agricultural knowledge, publicly available data, existing aid networks, and perhaps most importantly, the widespread adoption of Web 2.0 and mobile phone technologies. As this paper outlined, the success of a CS-driven approach to development will depend largely on sustained public support, the coordination of new and existing efforts, and fostering the automation of some analytical processes. While the suggestions for policy discussion offered here are only preliminary, it is within the purview of policymakers to foster the adoption and success of such an approach.

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[64] Munyi, "Plant Variety Protection Regime in Relation to Relevant International Obligations."

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