Seeds of Silicon: Internet of Things for Smallholder Agriculture

MIT D-Lab
Comprehensive Initiative on Technology Evaluation
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Acknowledgments

This work relied heavily on many people who are taking on the challenging task of growing food on small farms and improving services for farmers. The authors would like to thank the farmers, agricultural extension agents, and researchers who graciously welcomed us to their farms, offices, and project sites, including Boniface Akuku, Chris Bartonjo, John Gitonga, Ishmael Gure, Styvers Kathuni, Boniface Kamathi, Linus Kosambo, John Maina, Ciira Maina, Jared Makario, Daniel Mokrauer-Madden, John Mwirichia, Wanjiku Ng'ang'a, Paul Njuguna, Christy van Beek, Eli Pollak, Purity Wanjiku Thumbi, Neha Juneja, and Rikin Gandhi. We would like to thank our colleagues at MIT D-Lab who assisted us with connections to the sector, refined our field research methods, and review of this report, including Rich Fletcher, Megha Hegde, Elizabeth Hoffecker, Kendra Leith, Eric Verploegen, Sher Vogel and Libby Hsu. We would also like to thank Daniel Frey and Bob Nanes for their leadership and support, and Nancy Adams for communications support. Yashoda C and Tusher C provided support for our work in India, and Hubert Kimani and Lilian Lungo in Kenya.

Finally, we would like to appreciate our mentor Dorn Cox for responding to our many questions, introducing us to sector experts, and in-depth review of this report. We would also like to thank Craig Jolley, Nicole Bridge, Katie Hauser, and Maggie Linak of USAID for their support during this project.

The title of this report, “Seeds of Silicon,” was inspired by “Seeds of Gold,” a weekly pull-out magazine published by Kenya’s Daily Nation newspaper. Seeds of Gold features articles on farming topics and stories about innovative farmers, and is read by farmers across Kenya.

Cover photos: Left: Farmer Emmanuel Biketi, Horticulture Manager at Kikaboni Farm in Olooloitikosh, Kenya with an Upande temperature and relative humidity IoT device. Right: Drip irrigated vegetable cultivation at Napuu 1 Drip Irrigation Scheme in Lodwar, Kenya.

MIT D-Lab works with people around the world to develop and advance collaborative approaches and practical solutions to global poverty challenges. The program’s mission is pursued through interdisciplinary courses, research in collaboration with global partners, technology development, and community initiatives — all of which emphasize experiential learning, community-led development, and scalability. D-Lab led the research design, development of survey instruments, data analysis, and preparation of the report.
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The Comprehensive Initiative on Technology Evaluation (CITE) at the Massachusetts Institute of Technology based at MIT D-Lab, is dedicated to developing methods for technology evaluation in global development. CITE is led by an interdisciplinary team and draws upon diverse expertise to evaluate technologies and develop an understanding of what makes them successful in emerging markets. The research summarized in this report has leveraged CITE’s methodology to identify current state of the art in IoT for Agriculture in Global Food Security Strategy (GFSS) countries, their challenges to implementation and recommendations to overcome these challenges.
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This report was made possible in part through the support of the United States Agency for International Development (USAID). The opinions expressed herein are those of the authors and do not necessarily reflect the views of USAID. Digital Development for Feed the Future was a collaboration between the Global Development Lab and the Bureau for Food Security at the United States Agency for International Development (USAID), focused on harnessing the power of digital tools to increase food security, meet nutritional goals, and end hunger. Feed the Future is America’s initiative to combat global hunger and poverty.
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Anish Paul Antony, Jennifer Lu & Daniel Sweeney, “Seeds of Silicon: Internet of Things for Smallholder Agriculture”, Comprehensive Initiative on Technology Evaluation, Massachusetts Institute of Technology, 2019. Accessed on [insert date] from [insert source]

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Summary

Smallholder farmers across the world play an important role in food supply. To feed a growing global population projected to increase to 9 billion by 2050, food production would need to increase by 70% compared to the 2005 baseline level [1]. The bulk of this growth in food productivity will need to come from developing countries [1,3]. The expansion of mobile connectivity and connected devices to rural and remote locations, availability and affordability of sensor technology for an broad range of applications, the reduction in data transmission cost, and advances in distributed computing capabilities are increasing opportunities to apply precision agriculture methods on smallholder farms [9]. The combination of these devices and services is called the internet of things for agriculture (IoT for agriculture). A number of barriers contribute to the low penetration of precision agriculture methods in smallholder farms in developing countries including the high cost of implementing solutions in remote areas, low awareness among farmers and agricultural extension services, and challenges in connecting ground measurements to improved farm productivity. The goal of this research is to better understand these challenges and the landscape of IoT for agriculture in developing countries, identify potential solutions, and highlight some examples of IoT implementation on smallholder farms.

This report captures the current state of IoT technology in smallholder agriculture in Global Food Security Strategy (GFSS) countries, challenges and opportunities, and our recommendations. Challenges and opportunities are arranged into four main categories of (a) sensor technology (access to components, sensor calibration, device design, access to advice and expertise), (b) implementation of the IoT system (IoT business model including a clear path toward attractive monetization, remoteness of location, connectivity, data transmission cost, and equity of access) (c) analysis and decision support (raw sensor measurements, smartphone penetration, and data transparency), and (d) other. The recommendations directed toward donors, including: USAID and similar organizations positioning themselves to fill a facilitation role in horizontal integration of companies and institutes with sector-specific knowledge, increasing the funding timelines on IoT for agriculture projects to enable accurate predictive data analytics, and facilitating a forum in GFSS countries similar to the Gathering for Open Agriculture Technology to promote exchange and collaboration; and toward implementers, such as identifying a farmer or an agriculture extension agent who can help with basic troubleshooting and IoT maintenance in an agriculture IoT project, implement basic onboard diagnostics for the IoT device to minimize maintenance visits, and conduct simple tests to check factory calibrated sensors in conditions as close to the implementation conditions as possible. This report was prepared with the expectation that the findings could be useful to shape and inform GFSS strategy and ongoing and new efforts by practitioners and donor agencies that work with smallholder farmers.

Terms and Definitions

One barrier that we found during our interactions with different people in farming and IoT is the confusion and misunderstanding that comes from the use of sector-specific jargon. The following is a non-comprehensive list of terms that are commonly used in IoT for agriculture, and unofficial, practical definitions in an attempt to clear potential confusion when reading this report. For some terms we found colloquial definitions from other sources that fit this purpose, and for others we propose our own.

Agricultural extension (aka. ag extension, farmer advisory service): Advisory services which integrate scientific research into agricultural practices through farmer outreach and education [17]. Services are classified into three types:

- Technology transfer: a top-down approach transferring advice in a linear fashion
- Advisory: a group approach involving experts advising specific problems
- Facilitation: an approach in which farmers identify their own problems and are assisted in determining solutions.

Application Programming Interface (API): A system of tools and resources in an operating system. In general, APIs allow different software programs to integrate easily so that a developer does not need to create an entire system from scratch. David Linthicum provides a more in-depth description of how to use APIs in IoT applications[1].

Aquaculture: A farming system which couples cultivation of crops and fish where water is fertilized with fish manure and applied to crops for irrigation and nutrient enrichment. *Aquaponics*, a subset of aquaculture, cultivates crops in a soilless media and water is cycled between fish ponds (fertilization) and growing beds (filtration).

Backend (aka server-side) Services: Also known as “server-side” (as opposed to “device” or “client-side” services), these are processes (e.g. data cleaning and analysis) that are applied to information (e.g. sensor data) after collection of the data, usually in an automated manner and with no visibility to the end user. Instead of carrying out an entire backend process (e.g. receiving, analyzing, and displaying data), external applications and services can be called through APIs (see above) to execute specific tasks. In the case of IoT in farming, sensor measurements can be transmitted to an internet cloud-based server where the data is cleaned and reduced to relevant indicators (e.g. DC volts to millimeters of rain).

Printed circuit board (PCB, aka board): A physical structure that supports and connects mounted electronic components (e.g. capacitor, integrated circuit, power supply, resistor, sensor) using conductive traces in a specific arrangement. PCBs are commonly made of a non-conductive substrate (FR4 epoxy-glass fiber

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[1] techbeacon.com/app-dev-testing/app-nirvana-when-internet-things-meets-api-economy

composite is most common) to ensure that components and voltages are isolated and electrical noise is minimized.

Dashboard: A common format in data and IoT for presenting processed information (e.g. in a backend process) to an end user, service receiver, provider, or customer. Relevant information and indicators are displayed in an understandable and efficient format and often updates in real time (e.g. precipitation trends and real-time temperature).

Information and Communications Technology (ICT): Broadly, all of the services and infrastructure that transmit, receive, and make use of information and data. The topic of this report, internet of things (see below), is a subset of ICT. Paul Beynon-Davies uses an analogy to a plumbing system which is summarized in Table 1 [59].

Data throughput (aka bitrate): Amount of data moved successfully from one place to another in a given time period and measured in bits/sec [59].

Table 1: Plumbing-ICT systems analogy

Attribute	Plumbing System	ICT System
Medium	Water	Data, analog and digital signals, radio-frequency waves
Supply	Water bodies, municipal service	The internet, databases, sensors, banks, retailers, etc.
Storage	Tanks, reservoirs	Data store -- e.g. data center, physical servers, cloud storage, memory
Transmission	Pipes, fittings	Communications infrastructure -- e.g. wires, wireless towers, satellite
Control	Valves	Communication protocols
Use	Washing, heating, drinking	Text and voice communication, information sharing, calculations, decision-making

Internet of Things (IoT): IEEE published a comprehensive report on many definitions of IoT [19]. For this work, we will reference the ITU version [20, 63] where IoT is defined as “a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.” IoT uses identification, data capture, processing, and communication abilities to reach different applications while fulfilling privacy requirements. IoT is a vision of “doing more with less.” [18] It is the integration of a network of low-energy, high-connectivity commonplace items enhanced by sensors and microcontrollers. Another definition is “An emerging concept in wireless communications whereby vast numbers of commonplace items throughout the world can be augmented with sensors and microcontrollers that will enable them to interact with each other and users, resulting in a completely immersive internet." [21]

Precision agriculture: a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique conditions found in each field while maintaining environmental quality [5]. Precision ag commonly uses on-farm sensors and earth observation measurements to inform farming practices.

Remote sensing (aka earth observation): the indirect measurement and surveying of physical, chemical, and biological properties of the Earth's surface using aircraft and satellites at a distance, relying on propagated signals [22]. Remote sensing has a variety of applications including environmental monitoring, agriculture, meteorology, and topography mapping. Sensors are attached to satellites orbiting the earth to make measurements, commonly capturing images within a specific frequencies of light and radiation (e.g. visible light, infrared). Modern satellites used for remote sensing can achieve an image spatial resolution of 10 meters enabling small plots of land to be detected and analyzed. NDVI (defined below) is commonly calculated using remote sensing data.

Long Range (LoRa): A long-range, low power, low-bitrate system of wireless communication commonly used in IoT infrastructure, enabling low cost, battery-powered applications for IoT [18].

WiFi: The common term for the 802.11b standard set forth by the IEEE used for the wireless connections of short-distance, local area networks (LANs).

Zigbee: The common term for the 802.15.4 specification set forth by the IEEE. It is simple and consumes less power compared to Bluetooth and WiFi wireless connection systems and commonly used in IoT applications due to its low cost of installation, operation, and maintenance [23]. Nodes stay in sleep mode when not transmitting or receiving, allowing for extended battery life [24].

Ethernet: The common term for the 802.3 specification set forth by the IEEE. Ethernet is commonly used in wired connections of local area networks (LANs).

Bluetooth: A wireless technology standard designed for low-power, short-distance, two-way communication between network devices [25] using ultra high frequency (UHF) radio waves.

IPv6 over Low-Power Wireless Personal Area Networks (6LoPAN): Similarly to Zigbee, 6LoPAN is a low-power protocol allowing small devices wirelessly transmit data over short distances using an internet protocol. It is often used in IoT applications, as it increases accessibility for the smallest devices [26].

Wide Area Network (WAN): A long-distance communications network. WANs connect several local area networks (LANs) [25].

Mesh topology: In this topology, a node such as a sensor device is connected to one or more than one other node [20].

Star topology: In this topology, all nodes are individually connected to a central network point.

Normalized Difference Vegetation Index (NDVI): NDVI is an indicator on a scale of -1 to 1 used as an indication of whether or not a remote sensing target contains vegetation. Plants absorb large amounts of visible light and reflect large amounts of near-infrared light. The wavelengths of visible and near-infrared (NIR) sunlight are measured and used to calculate the difference between reflected light (NIR) and red light to determine the amount of vegetation in an area [52]. NDVI is calculated using the equation below, where "NIR" is the amount of reflected light and "Red" is the amount of red light absorbed.

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

Smallholder farming: Lowder, Skoet & Raney [58] analyzed national census, labor, and agricultural data and found that classifications of farm type (e.g., family, small, large) vary around the world, with African and South Asian small farms being smaller than in other regions. Current estimates suggest that there are approximately 570 million farms globally, of which 12% are "small" (1-2 hectares) and 72% are "family farms" (<1 hectare) [58]. In practice, we found that smallholder farms can also be owned by a landlord and operated under a rental agreement or by hired laborers, and can have a land area up to approximately 5 acres. These slightly larger farms have some important characteristics that differentiate them from smallholder farms, including their access to a shared pool of resources such as water through irrigation systems, chemical fertilizer, manure, and input seeds. Some farms that are small in land area have access to any or all mechanized farm equipment, irrigation, micro-environment structures, crop inputs, and hired labor. It was not within the scope of this research to further clarify a definition of smallholder farming, but we acknowledge that small farming does not necessarily equate to subsistence farming and extreme poverty.

Technology stack: The suite of technologies that make up a hardware and/or software service. Layers in the stack are characterized by their function in the overall system. A technology stack in an IoT application would consist of a) device hardware, b) device software, c) communications, d) server or cloud platform, e) cloud applications, and f) client-facing front end or dashboard.

Introduction

In the 1930s, one farmer in the United States produced enough agricultural products to feed 4 people [56]. In 2019, after 80 years of agricultural and bio-science innovation, one farmer in the United States produces enough food to feed 155 people [56]. According to the International Labor Organization (ILO), approximately 1 billion people globally are engaged in agriculture [3]. While this number is declining, the demand for agricultural crops is expected to double as the world population reaches 9 billion by 2050 [2]. This would require an increase in agricultural productivity, especially from emerging economies [1, 3]. Advances in agriculture are enabling farmers to use technology to make precise decisions with better information about their soil, water, crop, and local climate, bringing a new dimension to agriculture [56]. However, access to and uptake of these advances is largely isolated to commercial-scale and cash-crop cultivation.

Smallholder farmers account for a large share of agricultural production in emerging economies and play a significant role in maintaining the genetic diversity of food supply and mitigating the risks of nutritional deficiencies and ecosystem degradation [4]. However, they face challenges from increasing climate variability, lack of ability to rely on generational knowledge, and pressures on farmland from urbanization. Farmer productivity in Global Food Security Strategy (GFSS) countries has generally increased in the past decade, however high poverty rates remain among small farmers (Table 2). Increasing access to cellular networks and internet, along with decreasing cost of data transmission could enable smallholder farmers to access new information and insights, and organizations to serve them with those data products.

Precision agriculture is a recent trend in farming practice that could address some of these challenges. An essential component in precision agriculture, ground measurements from low-cost, connected sensors are transmitted to web-based data storage and analytical services, and included with other sources of information to help farmers make decisions. This is called the internet of things for agriculture, and we will refer to these tools as *IoT for ag* throughout this report.

The overall goal of this research is to inform donors and practitioners about opportunities to augment farming practices and decision-making at the smallholder scale using information from IoT devices, and provide recommendations to further catalyze and improve this sector. However, this is not to say that a sensor can replace a farmer's experience and intuition. This report summarizes an assessment of the IoT for smallholder agriculture landscape, including:

- a summary of the approach used for carrying out this research;
- a summary of the current state of technology;
- a collection of key insights and challenges gathered from the IoT for agriculture sector;
- IoT for agriculture implementation examples; and
- a summary of relevant concerns about equity of access, data privacy, and potential directions of this technology over the next five years.

Table 2: Summary information for agricultural productivity, mobile phone, data and internet in GFSS countires plus India, China and the United States (Link to full table is available at the report site: d-lab.mit.edu/research/comprehensive-initiative-technology-evaluation)

Country	Population, 2018 (Mn) (a)	% Population employed in agriculture, 2018 (a)	Poverty rate among small farmers (%) (a) (e), *all rural	Avg size of agricultural holding (ha) (b) (c) (d) (e)	Crop production index, 2016 (2004-2006 = 100) (a)	Mobile cellular subscriptions, 2017 (per 100 people) (a)	Price of 1GB mobile data as a % of GNI per capita PPP (a) (g)	Smartphone penetration (% of Popn.) (h)	Individuals using the Internet, 2017 (% of population) (a)
Bangladesh	161.4	40	43	0.54 (2005)	146.4	92	0.64	16.1	18
Ethiopia	109.2	66	67	1.4 (2012)	187.6	38	5.30	11.2	19
Ghana	29.8	34	56	2.56 (2013)	154.3	127	1.27	24.0	38
Guatemala	17.2	29	75	0.94 (2006)	165.9	118	1.13	55.0	41
Honduras	9.6	32	63	11.2 (1990)	132.3	89	0.10	28.0	32
Kenya	51.4	57	49	0.86 (2005)	129.0	86	1.91	20,9	18
Mali	19.1	65	51*	3.3 (1980)	193.4	119	13.20	27.0	13
Nepal	28.1	70	35	0.7 (2003)	139.4	123	2.68	50.0	21
Niger	22.4	76	53	4.57 (2011)	235.7	41	8.83	25.0	10
Nigeria	195.9	37	44	0.85 (2013)	118.9	76	1.10	13.0	28
Senegal	15.9	32	57	4.3 (2000)	155.5	99	2.72	19.0	30
Uganda	42.7	71	27	1.51 (2012)	81.6	58	8.44	15.6	24
India	1352.6	44	26	1.3 (2000)	142.8	87	0.14	27.7	34
China	1392.7	27	7*	0.6 (2011)	144.2	104	1.16	55.3	54
United States	327.2	1	17*	179 (2018)	122.2	121	0.23	77.0	75

(a) World Bank Data, data.worldbank.org

(b) Food and Agriculture Organization of the United Nations, Family Farming Knowledge Platform, www.fao.org/family-farming/data-sources/dataportrait

(c) Lowder, S., et al. (2016), "The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide", World Development, 87, pp-16-29

(d) The Wall Street Journal, "Agriculture Journal: China Versus India by the Numbers", blogs.wsj.com/indiarealtime/2011/09/20/agriculture-journal-china-versus-india-by-the-numbers

(e) United States Department of Agriculture, "Farms and Land in Farms 2018 Summary", www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/farming-and-farm-income

(g) Cable.co.uk, Worldwide mobile data pricing: The cost of 1GB of mobile data in 230 countries, www.cable.co.uk/mobiles/worldwide-data-pricing

(h) Newzoo, "Top 50 Countries/Markets by Smartphone Users and Penetration", www.newzoo.com/insights/rankings/top-50-countries-by-smartphone-penetration-and-users

Approach

During the period of August 2018 to June 2019, this research used a combination of a literature review, key stakeholder interviews, broader community surveys, and implementation site visits to gather information about the current state of IoT technology for agriculture. The following is a brief description of each of these research methods.

The research questions that were prioritized are:

1. What is the current state of technology in agricultural sensors suitable for low-resource settings?
2. What are the challenges to entry for low-cost sensors, including but not limited to cost, availability of quality products in developing countries, resistance to change by farmers, and smartphone penetration?
3. What types of sensors are best suited for small-scale farmers?
4. What are the research needs and potential directions of technology development over the next 5 years?

Literature Review

The literature review gave the team an understanding of the current state of technology in agricultural sensors, challenges to the entry of low-cost sensors, and the types of sensors used in IoT for agriculture. The literature review also enabled the team to obtain an overview of sensors and IoT projects related to agriculture in both GFSS and non-GFSS countries, and obtain a comprehensive account of the different types of sensors used in smallholder farming.

Databases such as INSPEC, COMPENDEX, and Google scholar were used with a search for articles containing the keywords "IoT," "sensors," "agriculture," "smart farming," "smallholder farmers," "developing world," and "precision agriculture." Articles were considered for inclusion if they contained any data on the kind of sensor used, the sensor's integration to the internet, value proposition, and technological challenges in sensor implementation. The year 1994 was selected as the cutoff because this period largely coincides with the advent of the term "precision farming" defined by Blackmore and Brown [5]. Articles were excluded if they did not represent a robust source of information, presented data in a nonstandard manner, presented data already included in the analysis, or provided information only on the use of mobile-based apps that were included in the umbrella term "Information and Communications Technology" (ICT). The literature has been aggregated into a publicly available Mendeley account for easy reference[2].

In addition to the team's literature review, USAID also shared a number of documents related to the convenings they have gathered related to IoT for agriculture. The June 2016 "Low-Cost Sensors for

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[2] Mendeley group name: IoT for Smallholder Agriculture, www.mendeley.com/community/iot-for-smallholder-agriculture

Agriculture” meeting gathered sensor developers, large technology companies, government, academics, NGOs, and funders to explore the opportunities and challenges in applying sensors in smallholder agriculture, with a focus on the themes of technology, adoption, and ecosystem [60, 61, 62]. Notes, presentations, and connections to attendees from these convenings were a useful starting point for this project and are included in the literature library.

Stakeholder Interviews

The purpose of the key stakeholder interviews was to obtain an overview of sensors and IoT used in agriculture, and identify the gaps in understanding the value of IoT to smallholder farmers and potential directions for technology development in this sector. Through the key stakeholder interviews, the team was also able to identify cases of IoT for agriculture in the United States and in some GFSS countries. A complete list of key stakeholder interview questions can be found in Appendix A.

The key stakeholders include experts in the field of sensors for agriculture, including technology specialists, practitioners implementing these technologies, and policymakers. The information from the key stakeholder interviews is aggregated and presented to maintain anonymity. In total, 25 key stakeholders were interviewed. They were selected based on their knowledge in either the IoT sector or the agriculture sector, or were agriculture-related development practitioners in the field. These stakeholders were assumed to provide a valid representation of the current state of technology in the sensor and IoT for agriculture sector.

Surveys

Survey responses from 37 respondents not only served to triangulate the interview data, but also provided use case profiles and potential directions for technology development, thereby answering the research questions outlined above.

The surveys covered topics on understanding the broader sensor landscape by asking questions on types of sensors used in the agriculture sector, the challenges in deploying sensors, and potential technology directions. The surveys were sent to two sets of communities through recommendations gathered from key stakeholders, and several online communities for IoT and agriculture technologists. One survey was sent to communities in the US that are focused on sensors and their integration into precision agriculture. An example of this is the Gathering for Open Agriculture Technology (GOAT, goatech.org). GOAT was selected because they focus on the use of technology and IoT specifically in an agricultural context. The second survey was practitioner-focused and was sent to field practitioners either implementing or funding agriculture projects in GFSS countries.

Both the surveys can be found in Appendix B. The survey responses were collected using Google Forms. The quantitative data was analyzed using an open-source Excel-based content analysis spreadsheet developed by the energy resource group at D-Lab, and the qualitative data was analyzed using a conventional and summative approach to interpret meaning from the data. In conventional content analysis, coding categories or themes are derived directly from the text data, while a summative content analysis involves counting and comparisons, usually of keywords or content, followed by the interpretation of the underlying context [7].

Site Visits

Site visits were used to conduct a deep dive into several cases in which implementers were using IoT for agriculture in their work. The MIT CITE team used the site visits to validate findings from the literature review, stakeholder analysis, and surveys in four locations. The site visit involved observations and semi-structured interviews in India and Kenya, which allowed for a deeper dive into the two geographic areas. Given that the focus of this research was on GFSS countries, the team covered several cases in Kenya. The visits were used to validate research questions on the state of IoT in agriculture in Kenya, technological challenges, barriers related to cost and acceptance, value of IoT service to a smallholder farmer, potential directions of technology development, and issues related to ethics and privacy of data.

Figure 1: Anish Antony and Mr. Paul Njuguna from the Lodwar City Department of Agriculture during a site visit to the Napuu 1 Drip Irrigation Scheme in Lodwar, Kenya

State of IoT for Agriculture Technology

Modern-day agriculture depends on a multitude of physical and chemical measurements [9]. This is achieved through the use of sensors and IoT networks in farming. Based on this research, sensors in farming are mainly used to measure characteristics in soil, plants, atmosphere, and water.

While Figure 2 focuses on ground-based sensors, remote monitoring of agricultural farms is achieved through the use of satellites, small aircraft, and drones [8]. These technologies are useful in pollination, measuring data on the health of crops from indices like the normalized difference vegetation index (NDVI), monitoring for effects such as drought, and pest detection [8]. A list of sensors and the applications in which they are used is found in Table 3.

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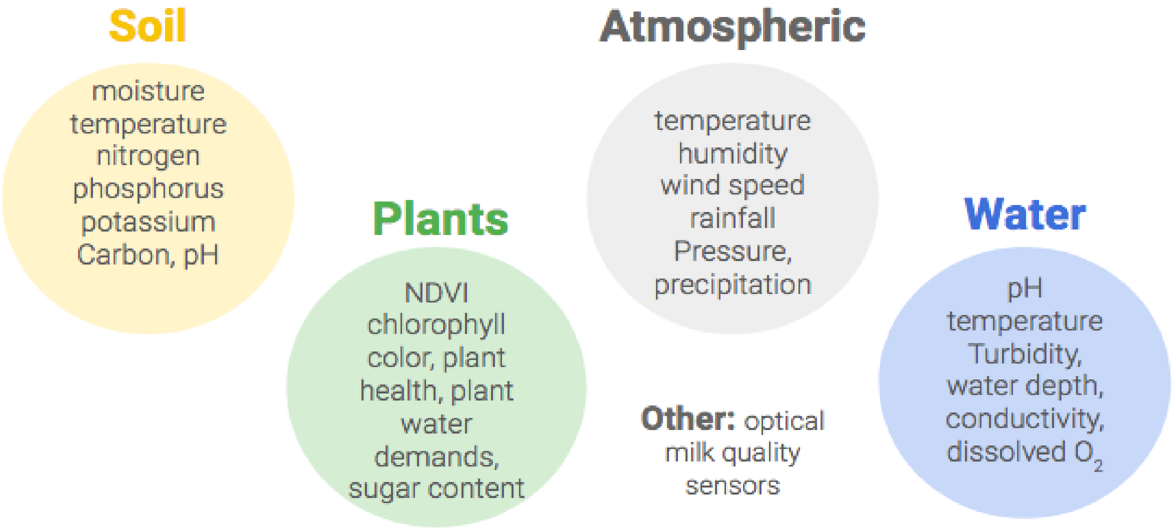

Figure 2: Most common sensors grouped according to their function.

Table 3: Sensors and their applications in precision agriculture and IoT [8, 10, 39, 40]

Sensor	Application	Countries with Documented Use
Load cell	Weight of harvested crops	USA
Mass flow	Irrigation water flow	USA
Ultrasonic	Spray boom height control	USA
Infrared	Seed counting, NDVI, chemical composition (NPK estimate)	USA
Accelerometer and gyroscope	Navigation and uneven terrain compensation, grain loss	USA
LASER	Crop height measurement	USA
Magnetic flux	Electrical current and power consumption, used to detect the running of a motor to pump water for irrigation purposes	Kenya
Electrical capacitance	Grain or soil moisture content, ambient air humidity	USA
Photoelectric	Volume of harvested grain	USA
Electrical conductivity	Soil moisture content, milk quality, soil and water pH	Kenya
Thermocouple, thermistor	Wet bulb temperature, seed and crop storage, greenhouse monitoring, soil temperature	Kenya, Uganda, Senegal
Image	Livestock and predator monitoring, crop records, time lapse	USA
RFID	Animal records, feed metering supply chain tracking, asset tracking	USA
Electrochemical	Ethylene concentration in fruit and vegetable storage (apples and bananas), greenhouse CO2 concentration	USA, Europe
SONAR	Water level, grain silo level	Kenya, Senegal, Guatemala
GPS	Tractor navigation, animal tracking, wireless fencing, asset tracking	USA

The general flow of data in an IoT system is presented in Figure 3 [41], where the sensing device, such as a temperature, humidity, or moisture sensor, transmits data through a communication layer (Table 4) to the server for analysis, then on to the end user. Depending on the transmission range and the data rate (Figure 3) and the power consumption (Figure 4), the communication layer is divided into long-range Low Power Wide Area Network (Eg: LPWAN: LoRa, Sig Fox, etc.), short range (E.g.: Bluetooth LE, Zigbee and Z-Wave, etc.), cellular communication (2G, 3G, 4G and 5G), and satellite communication.

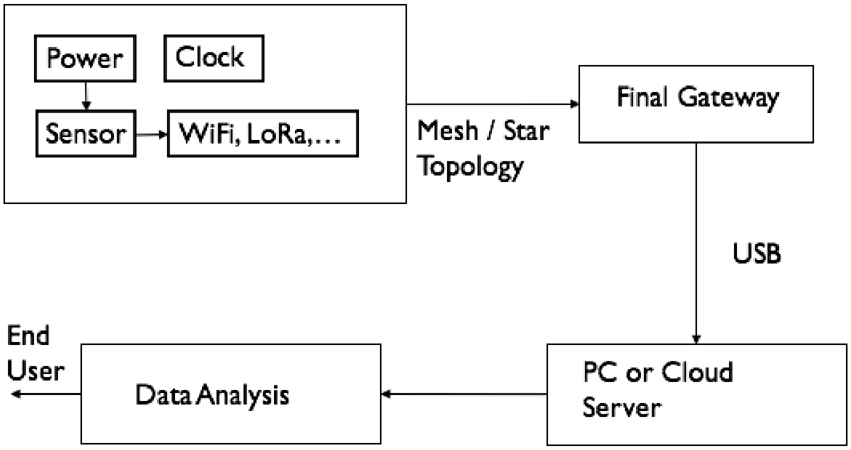

Figure 3: Overall sensor platform and communication

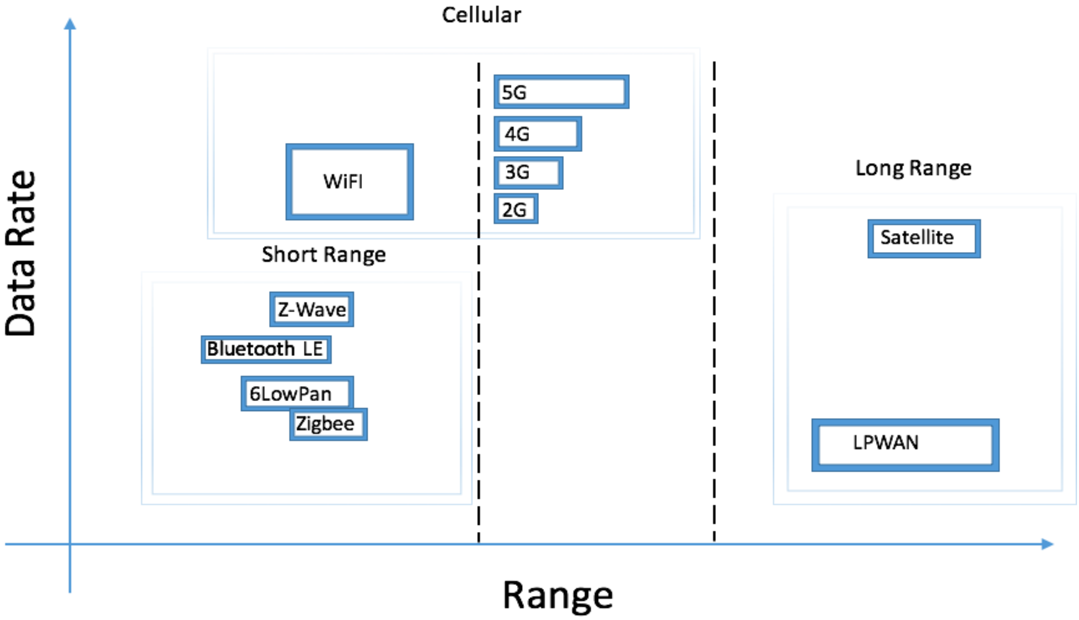

Figure 4: Range vs. data rate for common communication technologies [11, 12, 63]

Table 4 lists the current state of commonly used data transmission protocols, with the content highlighted in blue indicating a transmission protocol found by the team in Kenya and/or Senegal either through desk research, key stakeholder interviews, or survey analysis, and validated during our site visit to Kenya.

Considering the Kenyan context, sensors measuring ambient temperature, relative humidity, soil quality, and water quality (pH and dissolved oxygen) were the most commonly used combined with LoRa, WiFi, or cellular topology. This was mainly due to the low power and wide area network of LoRa, which made it suitable for certain low-power IoT applications such as obtaining data from temperature and humidity sensors scattered over a wide area on a field (<2 km from line of sight).

In our interviews with key stakeholders in Senegal and Kenya, we found a greater acceptance for sensors used in **aquaculture** and **aquaponics** than in crop growth. A combination of two factors were responsible, (a) System state: in aquaculture and aquaponics, the system state can be characterized with a small number of variables compared to crop growth. (b) Ease of intervention: a smaller area in aquaculture and aquaponics results in a more controllable environment. Farmers in both aquaculture and aquaponics could monitor the water quality data in a fish farm and make adjustments, such as changing the water when the pH level or dissolved oxygen content in the water varied from its desired value. These actions resulted in a visible improvement in the quality and size of the fish, benefiting the farmer.

Figure 5: Examples of wireless gateways used to receive data from sensors over WiFi and LoRa networks and then transmit to servers over broadband internet and cellular network

Table 4: IoT data transmission protocols explained

Standard	Description	Advantages	Disadvantages	Country
Zigbee [11, 12]	IEEE 802.15.4-based specification using mesh network topology and suitable for short- to medium-range communication (10-100 meters)	- Since the nodes can stay in sleep mode, they increase battery life - Can have >65,000 connection points on the Zigbee mesh network	- Short range - Cannot easily communicate with other protocols - Operates in the 2.4GHz ISM frequency band and therefore experiences signal interference from WiFi and Bluetooth	USA
Z-Wave [11]	Mesh network protocol that uses low-energy radio waves and proprietary radio system	- Can have up to 232 nodes - Devices are interoperable - Suitable for low-power devices, e.g., temperature sensors	- Not suitable for high-power devices, e.g., video cameras	USA
LoRa (Long Range) [13]	Long-range, low-power, and low-bitrate IoT communication system that uses star topology and unlicensed ISM frequency band	- Long range (10 km) - Low power consumption	- Actual line-of-sight range of ~2 km according to implementers - Large bandwidth for data transmission	USA, Kenya, Uganda, Senegal
WiFi [13, 15]	802.11 standards used for the wireless communications of short-distance local area networks	- Supported by most mobile devices, PCs, and broadband infrastructure - Easy to set up - Relatively inexpensive	- Short range (~20 m) - Bandwidth constraints occur when the number of devices or data increase, which are common constraints to other protocols as well	USA, Kenya, Senegal, Uganda
Bluetooth Low Energy (BLE) [16]	Provides reduced power consumption and cost operating at the 100 m range	- Supported by mobile devices and PCs - Operates in 2.4-GHz license-free band - Resistant to signal interference due to frequency-hopping scheme	- Low bandwidth - Short range (<100 m)	USA, India
SigFox LPWAN [14, 15]	Connects low power devices that transmit small amounts of data in a star topology on unlicensed ISM frequency band	- Low power consumption - Low cost because the network and computing complexity is managed in the cloud	- In some countries, operates in a frequency band that is susceptible to interference - Not supported in all countries	USA, Kenya
Cellular [40]	Network is distributed over land areas called cells, which are served by a fixed location transceiver. Majority of cellular networks use a star topology	- Supported by most mobile devices - Available globally with large and growing infrastructure - Long range	- Connectivity issues in remote areas due to weak signal strength - High power consumption	USA, Kenya, Senegal, Uganda

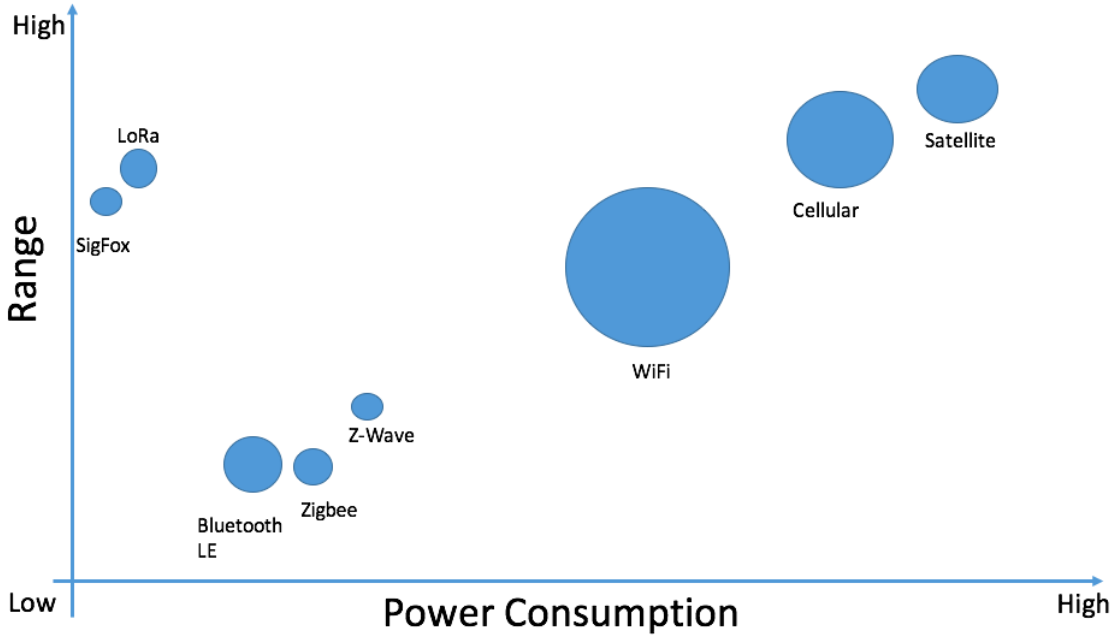

Figure 6: Power consumption vs. range for common communication technologies. The size of the bubble represents data throughput [11, 12, 63, 64]

In crop growth, however, the benefits were a greater challenge to visualize because the ecosystems were more complex, with many factors affecting crop growth that complicated the decision-making process in generating actionable recommendations based on the data collected using sensors. Additionally, in crop growth, the team found that with a greenhouse and temperature and humidity sensors, farmers were able to use the measurements to make adjustments in the greenhouse similar to aquaculture and aquaponics. One such example was a farmer growing tomatoes in a greenhouse. Based on sensor measurements, the farmer was able to adjust the watering conditions in the greenhouse and influence the ripening of the tomatoes.

Challenges, Opportunities, and Recommendations

In addition to presenting the current state of IoT for agriculture, we identify and understand the specific challenges that teams face when implementing IoT in smallholder agriculture applications, and wherever possible, opportunities for overcoming those challenges. The following section is a summary of challenges and opportunities separated into four categories: sensor technology (e.g., availability of components, accessibility of off-the-shelf products), implementation and use of IoT (e.g., finding the right location and partners), analysis and decision support, and other challenges. Wherever possible, we have identified practical advice, in most cases for implementers and in a few cases for donor agencies as well. The challenges are coupled with opportunities and recommendations that the IoT for agriculture community can consider to further improve implementation and promote appropriate use of sensors and IoT in smallholder agriculture.

Sensor Technology

Access to components: Off-the-shelf IoT technology is often unsuitable for the specific needs of agriculture applications, or too costly. For example, an off-the-shelf soil moisture sensor in Kenya sells for approximately 500 USD. Therefore, many local IoT companies develop their own solutions tailored to the requirements of their customers. Most hardware developers that we spoke with rely on e-commerce sites to source components (see Seed Topic: Sourcing Hardware Components). However, shipping time and cost can be high, and orders can get lost on the way, which delays the development process and can cause project timelines to run long and budgets to grow large. In most cities, analog circuit components are relatively easy to source in local markets, but extensive catalogs of modern digital components, ICs, and sensors are not available.

Implementer Advice:

- A good starting point is the local electronics repair and scrap market. Even in small towns, you can often find people repairing stereos and computers. They can sell you basic circuit components and may be able to direct you to other suppliers for more specialized components.
- Look for brick-and-mortar and online electronics stores in a city near you. In Nairobi, we found several new companies that are supplying components for hobbyist automation and robotics applications at prices similar to the larger e-commerce suppliers and with much shorter shipping times (e.g. in Kenya, store.nerokas.co.ke, ktechnics.com, pixelelectric.com).
- Consider designing a PCB (definition above) and having it printed for your prototype device instead of soldering components on a protoboard. There are a number of free, downloadable software tools for PCB layout (e.g., EAGLE[3], PCB Artist[4], DesignSpark PCB[5]). Then, submit your PCB layout to

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[3] www.autodesk.com/products/eagle/overview

[4] www.4pcb.com/free-pcb-layout-software

[5] www.rs-online.com/designspark/pcb-software

online manufacturers who can turn around small batches in 1-2 weeks (e.g., 4PCB[6], CircuitHub[7], Seeedstudio[8]). Board printing, just like 3D printing, is accessible for low-volume custom boards.

- Chances are that if you are using Li-ion batteries in your IoT device at scale, you will eventually need to import them. Many countries are now restricting import of Li-ion batteries and battery-containing devices, classifying them as “dangerous goods” and requiring a certification and/or proof of testing in order to import, especially for commercial quantities. Some battery manufacturers are offering certified products, which may be more expensive than non-certified products, but may save a lot of hassle. Search online for batteries that are in compliance with the standard test that your implementation country requires. Also, connect with other companies offering electronic products in your implementation country to see where they source certified batteries.

Device design: Smallholder farms are often in the most rugged and remote locations and require special consideration when designing a connected electronic device for long-term monitoring. Even when designers had taken measures to ensure the durability of their agriculture IoT product, we found several examples where sensors had failed or measurements were inaccurate due to unforeseen issues (e.g., nearby construction cut the power cable; bird droppings and dust blocked the PV panel). It is often impossible to predict all of the possible failure modes, but a few suggestions follow.

Implementer Advice:

- If you don’t have a working prototype yet, find a similar product, install and run it at a pilot testing site to see how well and for how long it functions.
- Invite a few farmers from the area where you will install your IoT to give input to the product design process. In addition to a product that is better designed for the application, you might find that farmers are more enthusiastic about your project and use the recommendations.
- Immediately start running a long-term functional test on your prototype in your workshop and run a test at a pilot site as soon as possible.

Figure 7: An Arable Mark device fitted with steel wires to deter birds from perching on the sensor.

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[6] www.4pcb.com

[7] circuithub.com

[8] www.seeedstudio.com/fusion.html

Seed Topic: Sourcing Hardware Components

Embedded electronics are everywhere, so it's likely that the component to meet your needs is available somewhere. Unless you are based in Shenzhen, you will likely have to order components from online suppliers. Here are a few sourcing suggestions and a non-comprehensive list of reliable, mostly US- and China-based suppliers that we use as of the writing of this report (keep in mind that this industry is evolving very rapidly!).

- Join, search, and query online communities to learn about what has worked for other developers. Some places to start are: IEEE IoT (iot.ieee.org), Gathering of Open Ag Tech (goatech.org), IoT StackExchange (iot.stackexchange.com), IoT Reddit (www.reddit.com/r/IOT), and Quora (www.quora.com). Even if you're not sure what to ask or contribute, set up an account so it is easy to participate when you are ready. Try to be a good community member and help respond to requests after you gain some experience.
- Found something that you want to try? If you have the budget, order a few possible solutions from a supplier in the list below. If you have limited funds, try requesting some samples from suppliers on Alibaba (www.alibaba.com) or look for other hardware tinkerers in your area that may have components you can borrow for prototyping. Community hacker- and maker-spaces are also a great place to start (a list of spaces can be found here: inventtolearn.com/resources-makerspaces-and-hackerspaces)
- Using a sensor that is sensitive to noise and interference? Consider designing a custom PCB and printing a small batch using one of a number of web-based services (see above). This can also be a good solution if your bread/protoboard is getting out of control.

Table 5: International hardware component suppliers

Supplier	URL	Notes
Adafruit	www.adafruit.com List of worldwide distributors: https://www.adafruit.com/distributors	Assortment of common electronics, sensors, microcontrollers, and tools. Especially well-suited for hobbyists and education. Good tutorials and support accompany most products.
Alibaba, Aliexpress	www.alibaba.com, www.aliexpress.com	Use AliExpress for small orders and general e-commerce purchases, and Alibaba to find your supplier at scale! Both ship worldwide with short delivery times (1-2 weeks) and inexpensive shipping.
Amazon	www.amazon.com International sites: https://www.amazon.com/gp/navigation-country/select-country	Now stocking most prototyping components, but you need to know what you're looking for. There are ~10 country sites in large markets outside the US, which tend to be more limited in selection, but are growing everyday. Some items can be paid with cash on delivery.
Banggood	www.banggood.com	Well-stocked e-commerce site with low prices on consumer electronics, variety of payment options.
Digi-Key Electronics	www.digikey.com International sites: https://www.digikey.com/en/resources/international	The best online source for electronics and circuit components. Currently not a large selection of sensors, but adding frequently. Order in small or large quantities with fast shipping times.
Ebay	www.ebay.com	Feeling lucky? Check eBay for liquidations and second-hand equipment, but don't buy your mission-critical items here. Can be especially good for second-hand tools and equipment. Look for highly-rated (>95% positive feedback) sellers. Now operating ~50 international sites.
Newark	www.newark.com	Comprehensive source for electrical, electronic, sensors, industrial control, and tools. You should know what you are looking for. Operate sites in ~50 international sites but no GFSS countries.
Seeed Studio Bazaar	www.seeedstudio.com International distributors: https://www.seeedstudio.com/distributors.html	IoT-focused supplier with a good selection of low-power communication components and sensors. Also offers PCB assembly services (5 PCBs for free!).
SparkFun	www.sparkfun.com International distributors: https://www.sparkfun.com/distributors	Assortment of common electronics, sensors, microcontrollers, and tools. Especially well-suited for hobbyists and education. Good tutorials and support accompany most products.

Sensor calibration: Most sensors measure an electrical proxy (e.g., charge, resistance, capacitance, signal delay, attenuation) that is related to the physical characteristics of interest (e.g., power consumption, moisture, pH, flow, liquid level). For example, most soil moisture sensors actually measure conductivity/resistance across two metal probes that are inserted into the soil. Correlating the measured resistance to soil moisture requires carrying out tests in controlled soil samples with known moisture content. More advanced sensors combine multiple measurements to account for other variables (e.g., soil composition) or compute aggregated indices (e.g., soil quality index). One reason for the higher cost of off-the-shelf sensors is that many undergo a factory test to calibrate the sensor against a standard or high-fidelity instrument. During our discussions, we found that implementers sometimes rely on uncalibrated sensor measurements or carry out on-site calibrations for each sensor installation.

Implementer Advice:

- For homegrown IoT hardware, developers should be able to provide measurement range and accuracy (% of maximum), and calibration curve with standard error information for each device model. If possible, perform long-term testing with multiple devices to understand if the signal may drift or attenuate, which could require maintenance or recalibration.
- Perform some simple tests to check factory-calibrated sensors in conditions as close to the implementation conditions as possible. For example, for a soil moisture sensor, compare field sensor measurements with a simple gravimetric test[9] and by checking across different sensor options[10].
- Arable published a thorough calibration document on the Arable Mark weather and crop monitor[11].

Access to expertise and advice: We were continuously impressed with the technical know-how of the teams that we spoke with and visited. However, many teams mentioned a lack of access to expertise and resources for technical and business challenges. Several engineers reported spending significant time “combing through StackExchange” for solutions to technical challenges. Some teams have hired experienced contractors to carry out short-term assignments, but later faced challenges in continuing those development flows on their own. This challenge was less significant for more highly-resourced IoT companies with larger technology development teams, often distributed across several countries.

Implementer Advice:

- In addition to StackExchange and similar forums, there are several online communities focused on the IoT and agri-tech sectors for idea exchange, support and recruiting team members (IEEE Internet of Things[12], Gathering of Open Ag-Tech[13]).

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[9] www.wikihow.com/Measure-Soil-Moisture

[10] www.kandrsmith.org/RJS/Misc/Hygrometers/calib_many.html

[11] assets.ctfassets.net/uzs63p7awoht/1L61IcXf7Ocw8uKSGsCAuI/d7969083e1273fbbb7732a0f14ae9fe4/Arable_Mark_-_Accuracy_and_Applications.pdf

[12] iot.ieee.org, www.linkedin.com/groups/5148323

[13] goatech.org

- More hardware-focused incubators and co-working spaces are being established to help hardware startups. Gearbox[14] in Nairobi is a good example of this, and came up as a resource in several of our conversations with IoT teams in Kenya. HAX[15] in Shenzhen provides hardware startup incubation at the largest electronics marketplace in the world, and larger opportunities for equity investment.

Opportunities for IoT companies to work on solving issues with sensor technology:

- To improve reliability and longevity in off-grid installations, add a small solar panel and charge control IC to your design, like one offered by Adafruit[16].
- Given the low-cost of memory and processing power, developers should consider added computation on the device (embedded computing) to reduce data payload during transmission and/or enable real-time feedback to farmers.
- With advances in satellite imaging for ground cover and radar for weather measurement, local, "ground" data will be increasingly important for verification and validation. Consider connecting your IoT measurements into a broader effort towards modeling and prediction within your implementing country.

Implementation of IoT

IoT business model: Everyone that we communicated with during this project agreed that the data collected from on-farm IoT sensors is valuable. However, identifying a specific customer, or buyer, of the technology is less straightforward, especially when the beneficiary of the technology is unlikely to have the means to afford the technology. For cash crops like coffee, flowers, and cocoa, agribusiness firms are often willing to invest in technology that helps improve product quality, yield, and traceability. However, for common staple crops grown on small farms, the value proposition is less obvious and return on investment is not easy to determine.

Figure 8: John Maina's Grispa Agro Shop in Mwireri, Kenya, where farmers purchase seed and inputs. John is also an agriculture extension agent for approximately 50,000 small farmers in Meru County.

Implementer Advice:

- In some cases, the farmer already has knowledge about the challenge, but lacks the resources or access to do something about it. Focus on the challenges that lack information and have a possible course of action for the farmer or their support ecosystem.
- A key to the success and expansion of the Kenya RAPID borehole pump IoT monitoring project is a partnership with

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[14] www.gearbox.co.ke

[15] www.hax.co

[16] www.adafruit.com/product/390

county government ministries and efforts to include IoT services in their annual budget.

Remote locations: The IoT for agriculture implementation sites that we visited in Kenya had few things in common, but one was that they were all remote and difficult to access. This can drive the cost of IoT services up if technicians need to regularly visit the farms and meet with farmers and agriculture extension agents.

Implementer Advice:

- Implement basic onboard diagnostics for the IoT device to minimize maintenance visits. For example, install a battery fuel gauge to measure and log state-of-charge; log the built-in microcontroller temperature; install a low-cost accelerometer to track movement and force.
- Identify a local farmer or agriculture extension agent who can assist with basic sensor maintenance and troubleshooting. In the example describe below, the horticulture manager at Kikaboni Farm is able to carry out some maintenance tasks (e.g., resetting the mobile network gateway).

Poor connectivity: The expansion of mobile network coverage has significantly improved connectivity in remote and sparsely populated areas around the world. However, in certain instances there are bandwidth issues with data transmission even with a high-signal strength.

Implementer Advice:

- Check mobile network coverage in your implementation area. Steve Song has compiled a thorough repository of resources on network connectivity and coverage, including the latest GSMA connectivity maps and user-contributed data from the Nperf network diagnostic application[17]. Keep in mind that maps generated by mobile network operators can sometimes represent best-case predictions of coverage.

Data transmission cost: The expansion of internet connectivity and mobile network coverage has decreased data transmission costs in remote Kenya.

Implementer Advice:

- The use of satellite technology for data transmission and the rollout of LPWAN IoT networks by groups such as Liquid Telecom should decrease the cost of data transmission to 1 USD/year/sensor device, depending on usage [14, 15]. Implementers are also looking at utilizing new satellite-based data transmission services with the decreasing cost of satellite technology.

Vertical Integration: Many organizations we spoke with in Kenya are taking a vertical approach to providing an end-to-end solution to a smallholder farmer. While this may be an efficient approach from an organizational standpoint, in reality it may prove to be less effective in terms of project success. Implementing an IoT system in agriculture and providing a benefit to smallholder farmers requires the amalgamation of multiple actors working in a complex ecosystem. It may be a heavy task for a single organization to solve the challenge of improving yield or predicting disease infestation by working on multiple angles of this complex ecosystem, from manufacturing the sensors to deploying them to collecting

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[17] github.com/stevesong/awesome-connectivity-info/blob/master/README.md

data, and then performing the analysis to generate actionable recommendations that improve crop growth or predict the occurrence of a pest infestation.

Implementer Advice:

- Try to incorporate a horizontal structure with partnerships in which each organization offers specific expertise to solve the overall problem in a piecemeal fashion. For example, one company can focus on manufacturing and deploying the sensors, another on data collection and analysis using combined expertise in agriculture systems and machine learning.

Funder Advice:

- Our recommendation through this research is for donors like USAID, DFID, and similar organizations to position themselves to fill a facilitation role in connecting diverse groups with specific expertise to solve the overall problem. Organizations forming new partnerships could particularly benefit from guidance in negotiating agreements and contracts.

Complicated Ecosystem: Successful implementation often involves coordination of a large and sometimes complicated ecosystem of actors over a long timescale.

Implementer Advice:

- If horizontal integration is not possible, then the implementer should make sure that the team carrying out the work has a mix of data scientists, sensor experts, and agriculture experts.

Funder Advice:

- Grants that fund work on sensors and IoT in agriculture should be structured for longer time periods (5-7 years). This way, a reasonable time frame of data history is created from multiple cropping seasons, thus enabling pattern matching and predictive analytics.

Equity of Access and Data Transparency: Confusion on who owns the data collected using IoT is common. Many projects on the use of sensors and IoT in smallholder agriculture in Kenya were funded by external organizations. While equity of access is important, a few guidelines to use data responsibly are available[18]. Also see Seed Topics: Data Security in this report.

Implementor Advice:

- While a fair degree of consensus exists that the data collected ultimately belongs to the community, the project implementers must communicate the same with the funding agency and set expectations before project implementation.

Funder Advice:

- Make sure to communicate early with the project implementers and have clear guidelines on the data access, privacy, ownership and sharing mechanisms of the data with the community. The Principles for Digital Development includes many useful tools for planning an implementation[19].

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[18] www.usaid.gov/responsibledata

[19] digitalprinciples.org

Opportunities for telecom providers and private sector to work on solving issues related to the implementation of IoT:

- Telecommunications companies offering tailored IoT data transmission services
- Decreasing costs of data transmission over satellite
- Different organizations offering specialized skills that are complementary to others. An example is Gearbox (Nairobi) that offers support, space and tools for hardware companies.

Analysis and Decision Support

Raw Measurements: Raw measurements collected from sensors are difficult to reduce into actionable recommendations for farmers.

Implementer Advice:

- While information on temperature and humidity levels is easy to read on a dashboard, correlating the temperature levels with crop growth patterns requires an agriculture expert. Having an expert on the team to look at the data and suggest recommendations relating to important outcomes like crop growth and fruit ripening is a good practice.
- Invite a few farmers and agriculture experts from the area to provide input on (a) what kinds of recommendations would be useful and actionable to the farmer and, based on their inputs, agreeing on the data required to assist the farmer in crop cultivation; and (b) the best way for the farmer to receive the recommendation. Taking this human-centered approach would help improve farmer involvement in the project. It is important to note that in some locations, a farmer is limited by the availability of the product at the local store. For example, a soil quality sensor can display information showing that the soil is deficient in phosphorus, but the only fertilizer available at the local store might be rich in nitrogen. Thus, the farmer may have limited access to resources to implement the solution, even though the sensor data gives an accurate recommendation.
- While farmers and agriculture extension agents are extremely knowledgeable of their land and the local area, much of their daily work relies on intuition. While sensors and IoT are great at collecting information on the farmers' land at the microscale, the farmer and the agricultural extension agent will not be able to realize the full benefit of the system unless they are trained in interpreting the data collected by these IoT devices.

Smartphone Penetration: Many agriculture advisory mobile apps require access to a smartphone – this potential barrier is layered on top of access gaps such as geography, income, gender, etc.

Implementer Advice:

- While designing an app, make sure that the output and recommendations are reaching the intended audience in a format accessible to them.

Opportunities for the IoT private sector to work on solving issues related to analysis and decision support:

- Merge IoT ground-measurement with available earth observations (e.g., Planet, Landsat, and Sentinel)

- Measurements should correspond to common indices used by farmers and agriculture extension agents
- Explore the use of learning techniques to predict local weather patterns and provide better planting, decision support, automation, and harvesting advice to farmers

Other opportunities

Short Funding Timelines: Many sensor- and IoT-based research projects in smallholder farming are supported by two- and three-year grants from donor agencies. When it comes to farming seasons, this is a relatively short time period, so collecting quality data and making actionable recommendations is a challenge.

Implementer Advice:

- ICTworks publishes an online digest of funding opportunities for ICT projects, many of which are applicable to IoT for agriculture projects as of the writing of this report[20].

Funder Advice:

- Increase the funding timeline to five to seven years so as to include at least five cropping seasons. This creates a reasonable time frame of data history, enabling pattern matching and predictive analytics.

IoT revenue generation: Many agriculture IoT projects are grant funded, and figuring out clearly defined ways to monetize the information from the data collected will help ensure project sustainability. An example of a monetization pathway would be a fee-for-service model, in which an IoT company sets up sensors on a farm, data from which help improve farming yields and increase profits, which are then used to cover the system costs. An issue to keep in mind in such a system is the up-front cost and access to credit for the smallholder farmer. The benefits of such a system are usually experienced at the end of the growing season. Thus, pay-as-you-go models could offer advantages here (solar home systems being a successful example[21]), but would require careful thinking and planning about payment incentives.

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[20] www.ictworks.org

[21] www.usaid.gov/sites/default/files/documents/15396/USAID-PAYGO.pdf

Seed Topic: Hands-on IoT training for students

A common element to the most successful agriculture IoT projects we found was a dedicated and experienced team of technology developers and implementers, especially within the implementing country. Several IoT companies commented on the major challenge of finding new team members with some training in IoT and agriculture. There is a need for more training opportunities for students with an interest in IoT. Here are a couple of good examples that we found during our visit to Kenya.

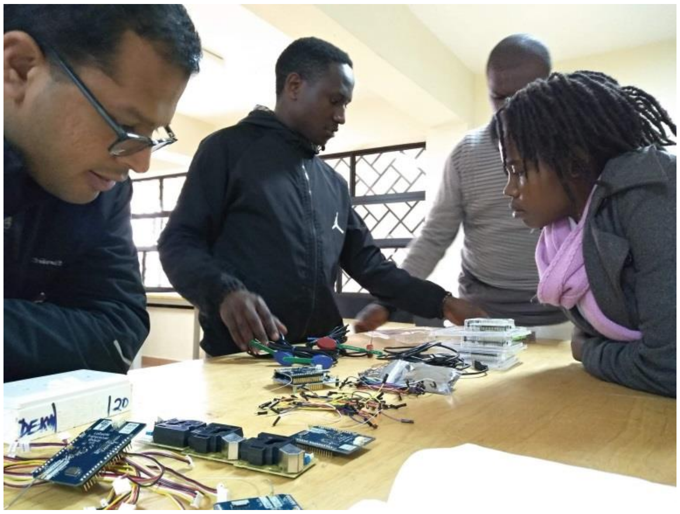

Figure 9: Data Science Africa scholar Jared Makario presents components from his IoT for agriculture project at the Dedan Kimathi University of Technology in Nyeri, Kenya.

<u>KENET and the University of Nairobi</u>: Although her main research area is natural language processing, Dr. Wanjiku Ng'ang'a from the University of Nairobi School of Computing and Informatics (profiles.uonbi.ac.ke/wanjikunganga) has become involved in projects that incorporate ICT and IoT tools. Dr. Ng'ang'a also chairs a special-interest group at the Kenya Education Network (KENET, www.kenet.or.ke) focused on computer science and information systems (SIG CSIS). Kenyan faculty can apply for travel and exploratory research grants through KENET, which can help reduce the barrier for faculty to enter new research areas that lack funding opportunities. Dr. Ng'ang'a strives to introduce her students to real challenges and solutions that can survive past the prototype, often evolving into a business and/or employment opportunity for the students.

<u>Dedan Kimathi University of Technology:</u> Dr. Ciira Maina, Senior Lecturer in the Department of Electrical and Electronic Engineering at Dedan Kimathi University of Technology, has been a leader in Data Science Africa (DSA, <u>www.datascienceafrica.org</u>), an Africa-wide program that provides hands-on data science and IoT learning opportunities for students. DSA scholars attend workshops where instructors from around the world teach them state-of-the-art methods and they apply those to local challenges through design projects. At Dedan Kamathi, Dr. Maina has hosted two DSA workshops, the inaugural event in 2015 and a more recent one in 2018, and offers continued opportunities for his students through courses and IoT projects at the university. One project that we were introduced to uses local environmental and soil moisture sensors to measure greenhouse growing conditions at the university farm. The student team has set up the IoT system and provides feedback through a web-based dashboard to farm staff, who are able to adjust growing conditions accordingly. Professor Maina’s students are eager to use the skills they have gained through DSA and their projects at Dedan Kimathi in their future careers and entrepreneurial pursuits.

Data, Security, Privacy & Protection

With the rise of IoT, privacy and cybersecurity policy are necessary to protect citizens' private and sensitive data [57].

Data Security

Data security relates to securing data against unauthorized access [57]. The CITE team conducted a survey with 17 respondents who have expertise in IoT and agriculture to figure out if data security (securing data against unauthorized access) was an issue of concern to practitioners and agriculture IoT experts. In the survey, 24% agreed and 12% strongly agreed that data security was a concern when using IoT for agriculture, while 64% remained neutral to concerns of data security.

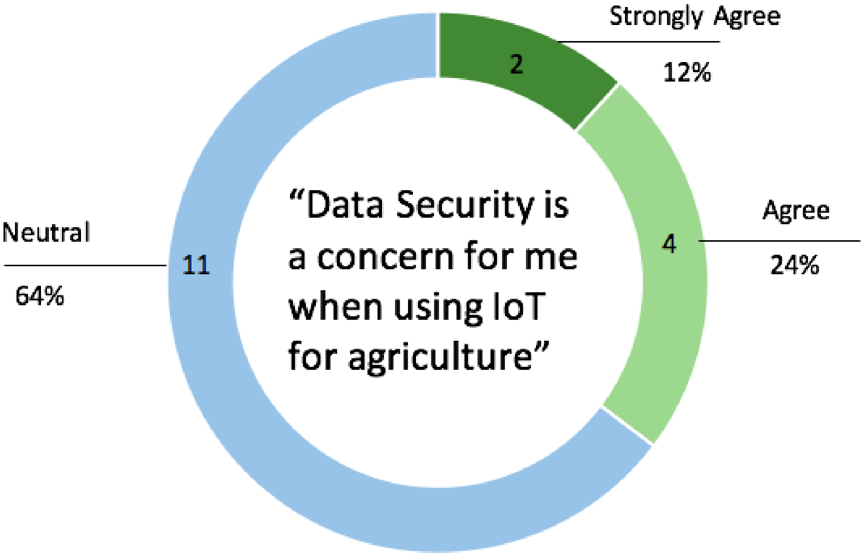

Figure 10: Data security when using IoT in agriculture (Source: survey of 17 respondents with direct experience in agriculture IoT projects)

Further follow-up with stakeholders revealed insights on the neutral rating for data security. Since the implementing organization set up the IoT system, they usually controlled access to data and believed that as the agriculture IoT project scope expanded and funding mechanism became clearer, they were willing to invest in third-party technology to improve data security measures.

Data Privacy

Data privacy deals with issues related to who has access to the data being collected and who defines who has access to it [57]. While questions on data privacy are still being answered in IoT systems set up in smallholder farms, our experience through our key stakeholder interviews and site visits helped us notice that in most cases, the organization implementing the IoT system usually has first access to the data, even if the data collected is from the farm of a smallholder farmer. Barring a few examples, most farmers we spoke with did not have direct access to the IoT data collected from their farm. They had to rely on staff from the IoT implementing organization to obtain access to the data. Factors contributing to this were: (i) the IoT project, including equipment, material cost, and staff time, were funded by a grant, and the IoT implementing organization was reluctant to share information with the farmer or make the data public unless they had explicit permission from the funder; (ii) projects were in a research phase, so the IoT implementers were dealing with challenges in data collection and transmission, and a large proportion of their time was dedicated to making sure the sensor and IoT devices worked well rather than on data interpretation, analysis, and sharing information with the farmer; and (iii) complex ecosystem-prediction algorithms in farming systems are yet to reach levels where they can accurately predict failure rates in crops, yield improvements, or occurrence of crop infestations based on the data collected, so there was a lack of clarity on what data/knowledge was important to share with the farmer.

In recent years, with the increase in the prevalence and usage of social media, GFSS countries are in the process of passing legislation concerning data privacy and protection. We acknowledge that while data collected from a farm is likely to have more in common with industrial or business data, and is not about discovering sensitive attributes about a person, for the purpose of this report we looked into data privacy legislation such as the General Data Protection Regulation (GDPR) passed in Europe and similar legislation in GFSS countries. GDPR matters, as there is a good chance it will serve as a template for privacy legislation in many GFSS countries, as well as the potential future implications it may have on the data being collected by IoT systems in GFSS countries.

General Data Protection Regulation (GDPR)

In May 2018, GDPR went into effect in the European Union. GDPR is designed to protect and empower a citizen's data privacy and is applicable in sectors ranging from banking to healthcare. The legislation emphasizes transparency of data, data access, and citizen awareness of data being collected [28]. The legislation mandates companies and organizations to register through the government if they use their customers' private data. Additionally, data from networks used by IoT companies must comply with GDPR on all levels. In general, with the rise of IoT, privacy and cybersecurity policy are necessary to protect citizens' private and sensitive data.

Table 6 summarizes the models and specific definitions that GFSS countries are following in writing their privacy legislation. The table also includes other possible implications of GDPR-modeled legislation in the country. Several countries in the African Union also adhere by the African Union Convention on Cyber Security and Personal Data Collection [30]. For African countries where no existing nationwide privacy legislation exists, the African Union legislation is listed instead [47].

Table 6: Data Privacy and Security Legislation in GFSS countries

Kenya [27]	- 2018 Data Protection Bill modeled after GDPR - Companies required to inform users of the type of data being collected - All data controllers and processors must operate on networks within Kenya, prohibiting cross-border processing
Bangladesh [48, 49]	- Data Security Legislation (2018) - Issues could arise with outsourced EU sensors (UNCTAD 2016) - Little current enforcement of data protection
Ethiopia [30]	- African Union Convention on Cyber Security and Personal Data Collection (2014) [30] - No specific protection laws in the country currently exist - Little current enforcement of data protection
Ghana [30]	- Ghana Data Protection Act (2012) modeled after GDPR [30] - Special personal data is defined as data which pertains to race/ethnic/tribal origin, political opinion, religion, physical/medical/mental condition/DNA, sexual orientation, and offences - Data controllers must register their activities and all processing of personal information must be registered - Outlines formation of a Data Protection Authority
Guatemala [32]	- Public Information Access Law (2003) - Little current enforcement of data protection - Public Information Access Law protects government from abusing data, and legislators are looking to apply it to private companies [32]
Honduras [33]	- New privacy law currently being drafted, modeled after GDPR [33] - Existing privacy rights currently found in constitution in their rights-based data model - Sensitive data is defined as data which reveals philosophical/political beliefs, religious beliefs, private life, racial/ethnic orientation, and health/sex life - Honduran law is particularly remarkable in ensuring that companies provide fair access to citizen data: businesses have only 10 days to respond to access requests filed by citizens
Mali [51]	- Aspects of GDPR are influencing local laws - Rules enforced by Data Protection Authority modeled after GDPR - Data crossing borders must comply with both sides' data protection laws - Lack of rules regarding explicit consent
Nepal [28, 29]	- Aspects of GDPR are influencing local laws
Niger [28, 29]	- Aspects of GDPR are influencing local laws
Nigeria [37]	- Nigeria Data Protection Regulation (2019) modeled after GDPR [37] - Freedom of Information Act (protects citizen data from the government, though no data protection regulator) - Sensitive data is defined as data which reveals philosophical/political beliefs, religious beliefs, private life, racial/ethnic orientation, and health/sex life - 2019 legislation mandates that public and private organizations must make their data protection policies available to the general public [37]
Senegal [39]	- Data Protection Law (2018) modeled after GDPR [39] - Sensitive data is defined as data which reveals philosophical/political beliefs, religious beliefs, private life, racial/ethnic orientation, health/sex life, and social and economic identity - Data controllers must register their activities - Data crossing borders must comply with both sides' data protection laws
Uganda [40]	- Data Protection and Privacy Act 2019 modeled after GDPR [40] - Data controllers must register their activities - Data crossing borders must comply with both sides' data protection laws

Given that many GFSS countries are in the process of implementing legislation similar to the European GDPR, we foresee their implications in agriculture IoT along these major themes.

(i) - Right to Be Forgotten

Ensuring that companies are using farmer data effectively and lawfully, as well as giving farmers the right to access their own data and delete it [27]. In future agriculture IoT applications, companies will have to take precautionary measures and build in features on their IoT-based projects to ensure that the information collected by the IoT systems on farmer personal data (including details such as farmer name, farmer race and ethnicity, and farm location) can be deleted from multiple platforms when requested by the farmer concerned. Thus, companies may be faced with a technical challenge to automate the deletion of their data stored on multiple platforms.

(ii) - Data Localization and Transfer

The data localization provision requires that all data controllers and processors must operate on networks within the individual country. Kenya, for example, requires that all data controllers and processors must operate on networks within Kenya, prohibiting cross-border processing with the exception of “compelling, legitimate interests” [27]. As long as the IoT system does not collect data that discloses information about the person’s race, ethnic, or tribal origin, political opinion, religion, physical/medical/mental condition, sexual orientation, and offences, the projects should not fall within the purview of the Data Localization and Transfer laws. For the most part, IoT data for smallholder agriculture does not seem to fall into this category.

The authors would like to clarify that Table 6 is not an exhaustive list, and laws are subject to change, so it behooves the practitioner/implementer to track each country’s legislation and make sure the intended IoT project complies with the specific country’s laws.

Implementation Examples

India

Our research on the use of sensors and IoT outside the United States and Europe led us to India, a country with a population near 1.5 billion people and over 130 million smallholder farms [58]. A number of sensor and IoT projects have been deployed in smallholder agriculture in India. While our focus was on GFSS countries, the team decided to conduct a scoping study in India over the course of the project, mainly to identify and understand some of the factors that made India a hotbed for sensor-based innovations in the agriculture sector, and figure out if some of the enabling conditions from India could be translatable to GFSS countries. We interviewed several researchers and practitioners working in India, and in January 2019, the research team conducted a scoping study with the Microsoft FarmBeats and Digital Green collaboration currently using IoT with smallholder groundnut farmers in Ananthapur, Andhra Pradesh. Site visits were conducted to capture the technical and non-technical aspects of the project from the perspective of the implementation organizations involved.

Figure 11: Tusher Chakraborty from Microsoft FarmBeats and Yashoda C from Digital Green, with a Microsoft FarmBeats version 3 sensor unit in Ananthapur, India

Our research identified several factors that enabled precision agriculture-based projects in India:

- **Connectivity through mobile networks**: Mobile network penetration is fairly high in India, and the costs of data transmission through mobile network service providers are some of the cheapest in the world. With the advent of service providers such as Reliance Jio, mobile phone penetration rates have increased: around 800 million Indians now own a mobile phone [49] and mobile data plans for 1.5GB are available for as little as ¢32 [48]. This has helped IoT companies explore opportunities to work with sensors using cellular services for data transmission.
- **Market opportunity:** The large population density, population size, and increasing incomes of the Indian middle class make India a lucrative market for IoT providers; hence, local Indian start-ups

are working on precision agriculture projects in this sector alongside larger players such as Reliance, Tata Consultancy Services, and IBM India [46].

- **Investing ecosystem**: Much investment in the Indian agritech ecosystem by groups such as Omnivore partners and Aavishkaar is helping catalyze sensor and IoT-based projects [47].
- **Policies**: Agriculture accounts for 17.32% of India's GDP and employs over 50% of its population, but rising costs and falling crop prices have hurt Indian farmers. In view of this, a few local state governments in India are providing subsidies for new farm equipment that could be leveraged towards precision agriculture purchases [46].
- **Enabling ecosystem**: The government of India has a vision of doubling farmer incomes by 2022, and in working towards that goal has launched a scheme called "Start-up Agri India" to help start-up companies working in the agriculture sector in India [44, 45].
- **Academic institutions**: Some of the best academic institutions in India are working with farmers and setting up hackathons across the country to create precision agriculture technology to help farmers [44].

Based on the project framing to focus efforts on a GFSS country, and given our findings in India, the team looked into the list of GFSS countries that had factors in their landscape comparable to those found in India. Factors such as mobile network penetration of greater than 70% [48], high cellular connectivity, vibrant investment ecosystem, market opportunity, and policy and development goals such as the Government of Kenya's vision 2030 factored heavily in selecting Kenya as our country of focus for site visits.

Kenya

In May 2019, the research team visited Kenya to gather more information about the implementation of IoT in agriculture through in-person key stakeholder discussions and implementation site visits. Key stakeholder discussions followed a semi-structured format as previously described. Implementation site visits were coordinated in advance with staff from the implementing organizations, with a focus on capturing both technical and non-technical aspects of the project.

This section is comprised of:

1. A brief summary of the Kenya visit, the findings of which are included in the relevant preceding sections;
2. Six "implementation examples," which we obtained by either visiting or speaking in-depth with implementing staff members.

Key stakeholders that we visited in Kenya included:

- Private sector IoT companies
- Private sector research organizations
- Government ministry officials
- Government researchers
- County and municipal government officials
- Agriculture extension agents
- University researchers

Kenya-specific themes: Similarly to most countries in the East African community, there is a large amount of attention focused on improving productivity on smallholder farmers. At a country level, there is growing interest in ICT and IoT solutions for challenges in smallholder agriculture. Startup companies are providing IoT services to large-scale and cash-crop farms. However, the sector is nascent, and the enabling ecosystem is still evolving.

Fish-vegetable aquaponics in Olooloitikosh

Farming system: Decoupled aquaponics (aquaculture fish farming coupled with hydroponic soilless vegetable farming in a controlled environment).

Location: Olooloitikosh, Kajiado County

Ecosystem and roles:

- Upande[22]: Private company based in Nairobi; technology developer, implementer, and IoT service provider
- Kikaboni Farms[23]: Organic farm supplying tilapia and vegetables (tomatoes, leafy greens) to Nairobi supermarkets; IoT service customer, IoT beta testing site, and aquaponics experts

Challenge addressed: Kikaboni Farm staff lacked the tools to monitor and maintain the sensitive fish and vegetable growing environments, resulting in underproduction, occasional loss of product, and inability to understand the underlying cause of these challenges.

IoT implemented: Upande Vipimo water (temperature, pH) and greenhouse environment (temperature, relative humidity) sensors. Sensors are powered by 3-10 W solar PV panels.

Data transmission: Sensors have embedded LoRa modules that transmit to an on-farm, mobile network-connected gateway that uploads data to Upande cloud-based servers.

Information feedback model: Custom dashboard and mobile application with real-time and measurement trends.

Service model: Upande develops, installs, maintains, and upgrades the IoT technology and back-end analytics. Kikaboni Farms pays for the service.

Keys to success:

- Clear buyer of IoT: Kikaboni Farm operates at a scale and quality where they are profitable and can afford to purchase IoT services.
- Data interpretation: The horticulture manager regularly monitors the

Figure 12: A Upande Vipimo T/RH sensor in the aquaponics greenhouse at Kikaboni Farm

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[22] www.upande.com

[23] www.kikaboni-farm.com

measurements via an online dashboard and has the expertise to interpret the measurements and make necessary adjustments to optimize the farming system.

- Immediate improvement: After installing the first set of IoT solutions, the horticulture manager was able to identify the cause of recent crop losses and implement a change to address this, which was also confirmed by the IoT measurements. The improvement in lettuce plant health was very clear (Figure 13).
- Collaboration: Upande and the horticulture manager maintain close communication to help identify problems and implement changes.
- Pull instead of push: Kikaboni Farm continues to request changes and additions to the IoT service, rather than Upande having to convince the farm to try new approaches.

<u>Risks</u>: While both the local horticultural manager at Kikaboni and the Upande staff have immense knowledge in their respective fields and collaborate effectively towards project success, a risk to the project may be staff turnover.

Figure 13: Lettuce plants growing in the aquaponics beds before (left) and after (right) improvements to the growing environment

Flood detection on Mara River in the Maasai Mara

Figure 14: The Mara River in Maasai Mara National Reserve (left), and a SONAR level sensor installed on a bridge over the Mara River (right)

Farming system: Smallholder agriculture, pastoralism

Location: Maasai Mara Reserve in the Great Rift Valley

Ecosystem and roles:

- Upande: Private company based in Nairobi; technology developer, implementer, and IoT service provider.
- Maasai Mara Reserve
- County Government: Manages the reserve; grants permission for monitoring activities on the reserve.
- Maasai Mara University (MMU): University based in Narok, Kenya. Hosts community meetings and workshops on river and wildlife monitoring and mapping.

Challenge addressed: With little vegetation in the Mara River watershed, rainwater can cause a rapid rise in the river level, which results in flooding and destruction. Low bridges over the river are often submerged during high-water events, sometimes isolating communities for multiple days at a time.

IoT implemented: Several Upande SONAR river level sensors mounted on structures above the river (bridge, etc.). The sensors are powered by 3-10 W solar PV panels.

Data transmission: Sensors have embedded LoRa modules that transmit to mobile network-connected gateways connected to grid power supply (with battery backup) and upload data via mobile network to Upande cloud-based servers.

Information feedback model: During high-water events, downstream farmers are alerted to remove water from the river using irrigation pumps to reduce the water level.

Service model: Upande develops, installs, maintains, and upgrades the IoT technology and back-end analytics. The initial equipment and installation was grant funded, and ongoing maintenance and back-end services are provided by Upande.

Keys to success:

- Local buy-in: Sufficient buy-in from the Mara County government to permit the IoT installation and regular maintenance.

Risks:

- There is little sustaining this project other than the dedication of stakeholders, including Upande and MMU, to keep the existing installations operating.
- High staff turnover in the county government with the risk that new employees will not be supportive of this project.

Maize cultivation in Nanyuki

Farming system: Smallholder farming (maize, potato, etc.)

Location: Nanyuki

Ecosystem and roles:

- Arable Labs[24]: Private company based in USA; technology developer
- University of California, Santa Barbara (UCSB): University based in USA; lead research organization and liaison to farmers and agriculture extension agents
- Mpala Research Centre[25]: Private research and conservation organization based in Nanyuki, Kenya

Figure 15: Boniface Kamathi (Mpala Research Centre) and farmer John Mwirichia discussing the Arable Mark device installed on John's farm.

IoT implemented: Arable Mark: Ambient Temperature, humidity, precipitation, NDVI, and Photosynthetic Active Radiation

Data transmission: Cellular to the cloud

Information feedback model: Custom dashboard and mobile application with real-time measurement trends

Challenge addressed: Farmers relied on rainfall data from the local weather station that was far from their farm and did not provide localized information. Using the Arable Mark, they get site-specific rainfall measurements and localized results in precipitation variability.

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[24] www.arable.com

[25] www.mpala.org

Service model: Arable Labs develops the IoT technology. UCSB and the Mpala Research Center install and maintain the IoT technology, including communicating the results to the local farmer.

Keys to success: This is an ongoing research project.

Risk: This is a research project supported by the U.S. National Science Foundation to answer basic science questions. Further funds would be needed to effectively translate the data collected into actionable recommendations that benefit farmers and agriculture extension agents in the region.

Greenhouse vegetable cultivation in Nyeri

Figure 16: Greenhouse Supervisor Purity Wanjiku inspecting tomatoes and a temperature, humidity, and soil moisture device in a greenhouse at the Dedan Kimathi University of Technology research farm.

Farming system: University staff maintain farms on their campus, growing tomatoes and coffee

Location: Nyeri

Ecosystem and roles: The Dedan Kimathi University of Technology in Nyeri, Kenya maintains farms on their campus that grow vegetables and coffee for internal consumption as well as distribution to the local market. Faculty at the School of Electrical Engineering provide the hardware, software, implementation, and analytics support.

IoT implemented: Greenhouse environment (temperature, relative humidity) sensors

Data transmission: LoRa to an internet-connected gateway, transmitted to local servers

Information feedback model: Custom dashboard and mobile application with real-time and measurement trends

Challenge addressed: The university farm staff lacked the tools to monitor and maintain the vegetable-growing environments, resulting in underproduction and under-ripening of vegetables.

Service model: Faculty and students from the university developed the sensor and IoT technology as a research project on the university-maintained farm.

Keys to success:

- Data interpretation: The greenhouse supervisor monitors the measurements on a daily basis and has the expertise to interpret the measurements and make necessary adjustments to optimize the farming system.
- Immediate improvement: After installing the first set of IoT solutions, the farm manager was able to identify the cause of under-ripening tomatoes using the data obtained from the sensors, and implemented a change to address this issue, which was also confirmed by the IoT measurements.

- Collaboration: The lead faculty researcher and his student maintain a close relationship with the greenhouse supervisor. Additionally, the greenhouse supervisor is willing to experiment with new technology on the farm.

Risk: There is good potential for Dr. Maina's group at Dedan Kimathi University of Technology to carry out impactful research. Steady funding is needed to build a pipeline of work given their expertise, location and access to research agriculture facilities.

Community farming in Turkana County

Figure 17: Drip-irrigated vegetable cultivation at Napuu 1 Drip Irrigation Scheme in Lodwar, Kenya (left), and a SweetSense gateway mounted on solar PV panels that transmits solar irrigation pump usage data to an online server via cellular or satellite data (right)

Farming system: Small-plot horticulture on shared land

Location: Lodwar, Turkana County

Ecosystem and roles:

- Millenium Water Alliance: Lead implementing organization for the Kenya Resilient Arid Lands Partnership for Integrated Development (Kenya RAPID), a large, public-private partnership among several organizations to coordinate water resource and rangeland management in northern Kenya (Garissa, Isiolo, Marsabit, Turkana, and Wajir).
- SweetSense Inc.: IoT technology company based in the USA with regional staff in Nairobi; technology developer, implementer, and IoT service provider.
- Turkana County Ministry of Agriculture: Provides and maintains land and irrigation infrastructure and training for community farms, including a farm site and community water supply at the Napuu Aquifer Site.
- Water Resource Authority: National government agency that permits access to water resources, including drilling of boreholes.

Challenge addressed: In the past 10 years, vast underground freshwater reserves have been discovered in northern Kenya, the Lodwar Basin Aquifer and the Lotikipi Basin Aquifer. If properly managed, these reserves could supply area communities with water indefinitely. The Kenya RAPID project was established to develop and implement an approach to sustainable management. One challenge that the project addresses is poor reliability of water pumping infrastructure for communities. The solar-powered borehole pumps experience equipment failures and long repair times, leaving communities without water for drinking and irrigation.

IoT implemented: Electrical current sensors that monitor solar borehole pump operation.

Data transmission: Motor current sensors are wirelessly connected to a nearby SweetSense gateway, which transmits data via cellular or satellite data to an online server.

Information feedback model: Data is aggregated and compiled into a database with a front-end dashboard accessible to county government staff responsible for maintaining the borehole pumps. The real-time pump status has reduced the down-time and repair intervals of these boreholes. Custom dashboard and mobile applications with real-time and measurement trends indicate the operational status of an electric pump motor.

Service model: SweetSense develops, installs, maintains, and upgrades the borehole pump monitors and data analytics service for Kenya RAPID. Participating county government officials are trained by SweetSense on how to use the dashboard for monitoring and repairing their pumps. Having now been in operation since 2015, machine learning can be used to predict pump failure and further improve the county water services.

Keys to success:

- Given the utility of this IoT solution for providing reliable water supply to communities, the county government has added installation and maintenance of the sensors as part of the annual budget ensuring long-term financial sustainability.
- This project involves a large ecosystem of actors with different roles and areas of expertise, and good coordination from the lead organization.
- Sweetsense has a large presence in the academic literature with many well-documented and successful IoT implementations. They benefit from collaborations with academic institutions and access to government funding in the United States.

Risks:

- The overall Kenya RAPID project is sustained largely on grant funding that could impact the use of the IoT solutions if discontinued.

Additional resources:

- Kenya RAPID fact sheet[26]
- Article: "Quantifying increased groundwater demand from prolonged drought in the East African Rift Valley"[27]

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[26] www.usaid.gov/sites/default/files/documents/1860/Kenya_Rapid_fact_sheet_2019.pdf

[27] doi.org/10.1016/j.scitotenv.2019.02.206

- Article: “Improved Drought Resilience Through Continuous Water Service Monitoring and Specialized Institutions—A Longitudinal Analysis of Water Service Delivery Across Motorized Boreholes in Northern Kenya”[28]

Fish farming in western Kenya

Farming system: Smallholder fish farming

Ecosystem and roles:

- Liquid Telecom: A pan-African telecom group that supplies fiber optic and satellite services for MTN, Bharati Airtel, and Vodafone. They developed an IoT network in Kenya to monitor and protect freshwater fish populations.
- Kisumu Innovation Technology Hub Lake Hub and Rio Fish: Developed the iOS and Android app called AquaRech.
- RioFish: Local fish farming group in Western Kenya.
- Sigfox: IoT Service provider using a Low Power Wide Area Network.
- Western Kenya fish farmers: The partnership between Liquid Telecom and Sigfox plans to equip 5,000 western Kenyan farmers with the sensors and app by the end of 2019.

Challenge addressed: The pH and temperature sensors send data to the cloud on the water conditions in fish ponds. This data is then processed and, using this information, feeding instructions to farmers are sent through the AquaRech app.

IoT implemented: Temperature and pH sensors

Data transmission: Sigfox LPWAN

Information feedback model: An Android and iOS app called AquaRech is used to share data and send recommendations to farmers

Service model: Liquid Telecom, in partnership with Sigfox, is rolling out the IoT technology in western Kenya

Keys to success:

- Immediate improvement: Farmers see a direct impact following the AquaRech recommendations through a visible difference in the quality of fish. The fish grow faster and feed waste is eliminated.
- Buy-in from local community: The presence of a local fish farming group, RioFish, has helped bring about and sustain this partnership

Figure 18: Digital thermometer installation at Ramogi Institute of Advanced Technology (RIAT) Kisumu

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[28] doi.org/10.3390/su11113046

between Liquid Telecom and the western Kenyan fish farming community (it is important to note the role of Dave Okech, Founder of Rio Fish and the Founder of AquaRech).

- Collaboration: RioFish and the Liquid Telecom maintain close communication to help identify problems and implement changes.
- Long-term vision: The overall aim of this project is to reach 30,000 fish farmers in Kenya. Having this long term vision helps encourage participation from the current fish farmers, as they are aware that their input will help tailor the product and improve the fish farming community overall.

Figure 19: : Aquarech Digital thermometer installed at Nyabera Fish Cage Farm in Homa Bay

Risk: Sustaining this project depends on the dedication of multiple stakeholders, including low pricing from SigFox and Liqu, active participation from RioFish, and buy-in from the western Kenyan farmers.

Additional resources:

- Article: "The Dark Secret Of Lake Malawi: Trading Sex For Fish"[29]

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[29] www.npr.org/sections/goatsandsoda/2019/06/28/736296041/the-dark-secret-of-lake-malawi-trading-sex-for-fish

Conclusion and Recommendations

Overall, this research reinforces the great promise in implementing low-cost, robust IoT devices on smallholder farms. At the moment, applications for scenarios with easily detectable and actionable parameters offer more immediate promise and likelihood of uptake than measurements that are more difficult to interpret. Additionally, targeting measurements that address a significant pain point (e.g., water supply reliability) can ensure buy-in from and value to the people involved in a local agriculture ecosystem. A major remaining challenge is gathering sufficient quantities of data of the right type, from the right location, and with sufficiently well-informed analysis and understanding for farmers to take action.

To promote moving past the internet of thoughts, we have compiled several concepts that we think will help to advance the IoT for the agriculture sector and the people working in it.

Agriculture IoT forum: Establish a forum for organizations active in agriculture IoT to exchange best practices and explore partnerships that leverage individual strengths. While forums like the Gathering for Open Agriculture Technology and Farmhack Netherlands[30] have been useful in the US and Europe, some of the problems faced by agriculture IoT implementers in developing countries, such as long shipping times for products, poor quality of locally available components, lack of access to resources and funding, and challenges in importing products through customs, will be better addressed by creating a smallholder-farming-centered open agriculture tech forum.

Increase funding timelines: Increase the timelines of grant-funded projects to allow data collection from multiple cropping periods, thus improving the success and quality of the final output -- from more data to better pattern recognition and predictive analytics, leading to suitable actionable recommendations.

Horizontal integration: Rather than one company focusing on an end-to-end service involving technology development, implementation, and data analysis and recommendations, have multiple organizations collaborate together, so each company brings its specific expertise to solve the overall problem. Having a system set up in this way would better align the group to explore opportunities for funding from areas such as the USAID BAA process. Some of the key stakeholders we spoke with indicated that, while they were experts in a few aspects of IoT and agriculture, trying to work on the entire end-to-end process of an agriculture IoT ecosystem was stretching them thin, and they would prefer to work within their area of expertise and collaborate with others on areas where they lack expertise.

Promotion through local media: During our conversations with farmers and agricultural extension agents, we found that many learn about new and improved practices through local media targeted toward farmers. For example, The Daily Nation newspaper publishes a section called “Seeds of Gold” every Saturday, which highlights innovative farmers and businesses around Kenya. Newspapers and television stations in other countries also feature similar agribusiness programs. We also found that farmers are becoming more connected in general, such as through smart devices, but digital literacy is still relatively low, so disseminating information through familiar written or radio means can be effective.

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[30] www.farmhack.nl

Integration of ground measurement and earth observation: At the 2019 ICT4D Conference[31], there were a number of presentations on the use of new satellite-based imaging capabilities for agriculture applications including farm identification, soil mapping, and estimating crop health. Open-access satellite data from NASA/USGS (Landsat[32]) and ESA (Sentinel[33]) are certainly enabling a much clearer picture of remote and low-resource locations. Many researchers in the sector agree that there are new possibilities to explore when earth observation datasets are combined with ground measurement from IoT devices.

Student IoT training: Working in the ICT for agriculture sector requires a unique skill set, including both technical skills and an understanding of farm practices and farmer needs. We found that students studying engineering and computer science are either not exposed to opportunities or not well-equipped for careers in this sector. We also found several motivated faculty who organize programs that are providing Kenyan undergraduate and graduate students with hands-on experience in IoT for agriculture (see Seed Topic: Seed Topic: Hands-on IoT training for students). Programs like these are preparing students for careers in ag-tech, but are currently limited in resources and reach. Thus, bringing together agriculture and technology would pique the interest of a different population of students motivated to address agriculture challenges.

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[31] www.ict4dconference.org
[32] landsat.gsfc.nasa.gov
[33] sentinel.esa.int

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About the Authors

Anish Paul Antony is a postdoctoral associate at MIT D-Lab, Massachusetts Institute of Technology (MIT). He currently supports the development of low-cost energy access programs with universities and community-based organizations in South Asia. During his time in the energy sector, Anish has developed a keen understanding of how the sector works from end to end and provides lab- and field-based technical assistance for using sensor systems to collaborators across the developing world. Anish has co-authored several publications on renewable energy and grid stability issues and currently serves as a reviewer for the Journal of Renewable Energy and the UN IPCC Special Report on Global Warming of 1.5C supplementary report and is a judge for the MIT 200K Clean Energy Contest. Anish holds a PhD in electrical engineering from the University at Buffalo School of Engineering and Applied Sciences, where he designed a storage system for renewable energy systems and, through the Henry A. Panasci Jr. Technology contest, was involved in a landscape and market analysis of IoT devices that developed affordable, easy-to-install smart connected devices for remote data collection in the U.S.

Jennifer Lu is an undergraduate student studying mechanical engineering at MIT. Jennifer has been involved in MIT D-Lab projects since her sophomore year, where she has worked in teams to prototype a low-cost water filtration system for rural communities in Northern India and conducted energy use assessments and workshops in Nepal. Previously, she has worked as an engineering design intern at Natel Energy, where she designed a test rig assessing hydraulic turbine efficiency. She is currently a summer consultant in Navigant's Energy Cloud Transformation Team, where she is supporting projects including a demand response program evaluation and microgrid implementation analysis.

Daniel Sweeney leads biomass fuels and cookstove research at MIT D-Lab, Massachusetts Institute of Technology. Following D-Lab's approach, his work emphasizes "design with" as opposed to "design for," and is often in collaboration with community organizations and social enterprises that are serving their communities with household energy and improved cooking products. Dan's research areas are lab and field testing of stoves and fuels (D-Lab BurnLab), user research, remote sensors, pyrolysis and gasification, and appropriate machine design. He has been a co-instructor for D-Lab: Energy and a lead-instructor for an International Development Design Summit (IDDS) focused on cooking technology (IDDS Cookstoves 2016). Prior to D-Lab, Dan was a Fulbright Scholar at Luleå Tekniska Universitet. He holds B.S. and Ph.D degrees in mechanical engineering from the Colorado State University and the University of Utah.

Appendix A:
Key stakeholder interviews discussion guide

The following are points that are used to guide discussions with stakeholders:

- Introduce the project and goals of the interview:
  - Understanding the landscape of agriculture IoT, particularly low-cost sensors, applications and opportunities related to smallholder farms in developing countries, recent advances in technology, and gaps and challenges in need of further development
  - Relevant experience of the interviewee
  - Recommendations for other relevant projects or contacts
- What is your background and experience in IoT for ag? What types of IoT devices have you worked on and implemented at farms?
- What IoT applications have you seen that you think hold the most promise for smallholder farmers in developing countries? IoT applications you have seen that present challenges for use by farmers?
- From your perspective, what are the biggest gaps in understanding the value IoT technologies might offer to smallholders? What are the biggest opportunities?
- What use cases — e.g., monitoring soil quality, irrigation, pest control, etc. — are IoT technologies best poised to address for smallholders?
- Who do you see as the ideal or most likely user of these technologies? For example, are these technologies best suited to be used by the individual farmer, co-ops, agriculture extension workers, NGO workers, or someone else? At what price do you think these technologies would need to be available to be accessible to these different user types?
- Can you share experiences from specific projects? Documentation from those?
- What are the key technical and non-technical challenges?
- Do you know of cases where there have been implementation challenges related to, e.g., ethics, privacy, security, consent, ownership of data?
- What organizations and individuals should we be in touch with?
- Can we follow up with you?
  - Contact for further questions
  - If reasonable, engage as an adviser moving forward?
  - Ok to acknowledge in the report?
- Is there something that we can share back to stakeholders, or another way to appreciate their input and advice?

Appendix B:
IoT practitioner and researcher surveys

I) Survey to communities in the US that are focused on sensors and their integration into agriculture

MIT D-Lab is collaborating with USAID to conduct research around the landscape of low-cost sensors for agriculture. This survey helps us in directing our research to promising sensor models, with the overall goal of informing USAID feed the future strategy.

1. Date
2. Have you used the Internet of Things (example: monitoring of crops with sensors connected to the internet) and sensors in any form in agriculture production, aquaculture, or dairy farming?
3. If so, what applications did you use it for? Please include all applications (there should be separate boxes for people to respond)
4. What were you measuring?
5. Why were you measuring this?
6. What type of sensors and hardware did you use? [e.g., soil moisture, soil quality, temperature, water acidity -- Select all that apply]
7. Which communication methods did you use in your implementation?
   - ○ Zigbee
   - ○ Wifi
   - ○ LoRa
   - ○ Ethernet
   - ○ Z-wave
   - ○ 6LoWPAN
   - ○ Other (please explain)
8. Why did you pick this communication/topology over others?
9. Can you describe the overall connection from the sensor reading the data to how you viewed this data? Elaborate on all the stages involved [e.g., data from a soil moisture sensor through a zigbee communication layer onto a final gateway using a mesh topology]
10. How did you read the data that was measured? [e.g., tablet, PC, mobile phone, on the sensing device screen]

11. Can you explain the value you received from incorporating sensors and IOT into your farming process?
12. Are there any challenges to implementation of sensors and IOT in measuring for your applications?
13. If yes, what are the barriers?
    - ○ Cost
    - ○ Ease of use
    - ○ Battery life
    - ○ How to make use of the data
    - ○ Other, please explain
    - ○ All the above
    - ○ None of the above
14. In your opinion, what areas of improvement exist for IoT in agriculture?
15. Prior to using sensors and IOT for measurement in your farming practices, how were you measuring these data points?
16. Please indicate your level of agreement with the following statement: Data security is a concern for me when using IOT for agriculture.
    - ○ 5 = Strongly Agree
    - ○ 4 = Agree
    - ○ 3 = Neutral
    - ○ 2 = Disagree
    - ○ 1 = Strongly Disagree
17. What would you like to change to decrease your concern?
18. On a scale of 1 to 5, how interested are you in adopting sensors for your farming practices?
    - ○ 5 = Extremely interested
    - ○ 4 = Very interested
    - ○ 3 = Interested
    - ○ 2 = Somewhat interested
    - ○ 1 = Not at all interested
19. If you selected (1) or (2), what would make you more interested in adopting sensors? Why?

II) Practitioner-focused survey

MIT D-Lab is collaborating with USAID to conduct research around the landscape of low-cost sensors for agriculture. This survey helps us in directing our research to promising sensor models with the overall goal of informing the USAID feed the future strategy.

1. Date
2. What kinds of crops do you or the people you work with grow?
3. Do you use any form of Internet of Things (example: monitoring of crops with sensors connected to the internet) in agriculture (crops and livestock) or aquaculture in the region?
   - ○ If yes, can you describe this in detail?
   - ○ If no, why not? (Go to question 9)
4. Can you explain the value you received from incorporating sensors and IOT into your farming process?
5. Are there any challenges to implementation of sensors and IOT in your farming practice?
6. If yes, what are the barriers?
   - ○ Cost
   - ○ Ease of use
   - ○ Battery life
   - ○ How to make use of the data
   - ○ Other, please explain
   - ○ All the above
   - ○ None of the above
7. In your opinion, what areas of improvement exist for IoT in agriculture?
8. Please indicate your level of agreement with the following statement: Data security is a concern for me when using IOT for agriculture.
   1. 5 = Strongly Agree
   2. 4 = Agree
   3. 3 = Neutral
   4. 2 = Disagree
   5. 1 = Strongly Disagree

9. What would you like to change to decrease your concern?

10. Through your work, have you come across others in your region who use IOT and sensors in farming?

   - ○ If yes, can you give us an example and connect us to this person through phone/email?
   - ○ If no, thank you.