2023 International Conference on Earth Observation and Geo-Spatial Information (ICEOGI) | 979-8-3503-9672-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICEOGI57454.2023.10292956

# Internet-of-Things and Wireless Sensor Networks as enablers for soil observation in smallholder farms

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***Abstract*—Smallholder farms are known to be resource-constrained and remotely located, which makes in-situ data collection challenging. Typically, on-farm data deficiency arises and little support for farming decisions is one cause of poor production. Automated, precise, and affordable data collection and dissemination methods are vital to fill this data gap. The Internet of Things (IoT) and wireless sensor networks (WSNs) are tools fitting the bill, but they require careful design and deployment for local contexts.**

**Our work is an attempt to define an IoT-WSN system as a digital data infrastructure for in-season farm monitoring in rural smallholder farms. Design considerations are identified to enhance system reliability and robustness. A wireless communication protocol that runs reliably in a resource-constrained environment is identified, devices with ease of access, configuration, and maintenance were selected, and an appropriate sampling strategy to address a wide area with minimum resource consumption is designed. LoRa nodes with soil physical property sensors have been distributed among representative farm plots for data collection. And data was sent, autonomously to a back-end system over cellular communication. Our experience reveals the potential of the technology to generate as much required data as needed but with further careful design issues.**

***Index Terms*—Internet of Things, wireless sensor network, digital data infrastructure, data collection in smallholder farms, in-season farm monitoring**

## I. Motivation

In the absence of farm information systems and irrigation technology, smallholder farmers are vulnerable to variability in environmental conditions. Water excess and scarcity give particular concern because smallholder farming commonly applies rain-fed practices. Moisture and temperature are core soil attributes that may significantly affect farm productivity [1]. Soil moisture dictates the water content available to crops while soil temperature regulates the crop's nutrient and water uptake and thus determines plant growth [2]. These parameters should be monitored in the plant root zone and throughout the growing season, to allow the early-enough warning to the farmer of deteriorating conditions.

Data infrastructure is required for continuous field monitoring and informing farmer decision-making. Such becomes possible through data collection, storage, and analysis when sources like weather stations and soil sensors are put in place. Some research work in digital data infrastructure for smallholder agriculture has been conducted. Recent studies have focused on cost-effective data collection technologies such as remote sensing (RS), in-field sensors, and mobile phone applications. Full utilization of remote sensing products is challenged by the characteristics of smallholder farms (small, multi-cropping, extensive management, surrounded by other vegetation) [3]. The absence of calibration data and high levels of cloud cover may also hinder the full exploitation of RS technology. Small and inexpensive in-situ sensors are viable alternatives that can complement remotely sensed data and can be used for data validation [4].

Internet of things (IoT) and wireless sensor networks (WSNs) have considerable capacity to capture data more precisely, and affordably, and normally are easily deployed in harsh and infrastructurally deprived environments. With that, they are receiving substantial attention, from the scientific and industrial communities alike, for in-field data collection.

IoT and WSN can help the (near) real-time monitoring of farm parameters such as soil moisture and temperature. With such data acquired at the farm level, context-specific solutions can be designed that may help enhance farm productivity.

Prototypes, experimental set-ups, and theoretical frameworks in establishing IoT-WSN data infrastructure in smallholder agriculture are reported in several works [5, 6, 7, 8]. Our previous work presents an in-depth analysis and findings of such works [9] However, evidence shows that substantial gaps exist in the availability of and access to data services in the community. There is a need for further deployment of IoT and WSNs in actual farm plots, to create critical mass, build expertise and share in value. Real-time and remote monitoring of farms is critical as frequent field visit is often too challenging.

With appropriate design and implementation considerations, IoT and WSN can be utilized to achieve the timely generation of farm data and fill the data gap that exists in the wider

Funding for our work was provided by the Dutch organization for internationalization in education (Nuffic), the University of Twente, Faculty of Geo-information Science and Earth Observation (ITC) and the Ministry of Science and Higher Education of Ethiopia (MoSHE) under the Ethiopian Educational Network to Support Agricultural Transformation (EENSAT) project (CF13198, 2016).

farming community.

## II. Design and Realization

### A. Study area description

Northern Ethiopia is one of the most drought-prone and moisture-deficit regions in the country [10]. Especially South Wollo has a long history of food insecurity as most households are dependent on rain-fed agriculture. The rugged topography and irregular erratic rainfall have caused severe environmental and land degradation, soil erosion, and depletion of soil nutrients. These are the cause of low farm production.

Our work is conducted in two districts of the South Wollo zone: Dessie Zuriya and Kutaber. The two districts were selected because of the representative agroecology they present, the recurring poor farm productivity report but also their relative accessibility. According to the districts' agricultural offices, most households heavily rely on government support through the Productive Safety Net Program (PSNP) because of continued crop failures. The capital city of the zone, Dessie, is 400 km north of Addis Ababa and lies in between the two districts. Both districts are characterized by diverse topographic conditions with mountainous and highly dissected terrain and steep slopes. Summarized descriptions and maps of the study areas are presented in Table I and Fig. 1.

TABLE I
General information about the study area; Sources: Ethiopian Central Statistics Authority (population density), Ethiopian National Meteorology Agency (mean annual rainfall and temperature)

| Properties \ Districts | Dessie Zuria | Kutaber |
|---|---|---|
| Latitude | 11.238 | 11.030 |
| Longitude | 39.143 | 39.589 |
| Area [km$^2$] | 631 | 941 |
| Elevation range [m] | 1400–2900 | 2300–3500 |
| Total Farmland [%] | 47 | 38 |
| Total population | 126,805 | 201,433 |
| Population density [km$^{-2}$] | 135 | 319 |
| Mean annual rainfall [mm] | 1100 | 1300 |
| Mean annual temperature [°C] | 16 | 15 |

### B. IoT-WSN deployment design considerations

Cost-effective and less resource-hungry technologies are appreciated in the smallholder community. Scalability, transferability, ease of operation and maintenance, and pervasiveness also require consideration prior to technological interventions in the community. At the same time, it is unrealistic to expect any technology that provides all answers. A systemic approach to the design and implementation of the technology is required to address such needs with minimal trade-offs. Successful IoT-WSN deployment in this context depends on a careful design that articulates the different requirements and constraints of the farm environment. Specific design considerations can be categorized as physical, logistical, or technical. Each is briefly discussed below.

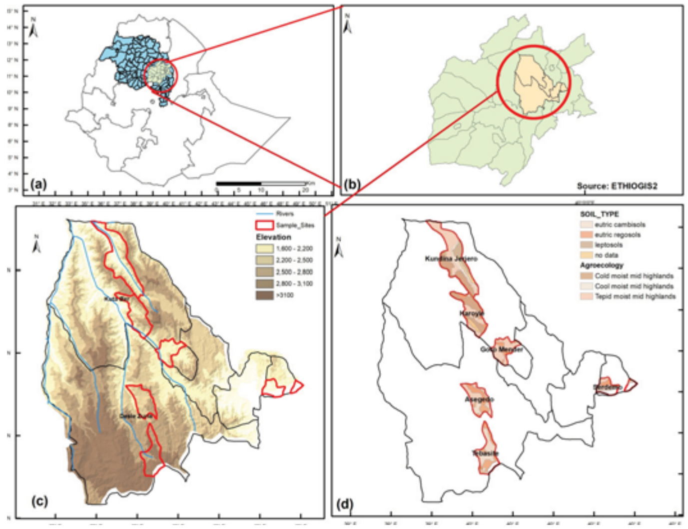


Fig. 1. Study area map (a) Amhara region, Ethiopia, (b) South Wollo Zone, (c) Target districts of the study with elevation, (d) major soil types and agroecology of sampled sites

**Physical considerations** Smallholder farms are often fragmented into multiple plots, dispersed in the landscape, with different crops on neighboring plots. This adjacency may imply plot similarity, but different crops may have different needs. In our specific Ethiopian context, farms are scattered over highly diverse topography. Such requires a wide WSN set-up with a considerable number of sensors, which means requires substantial investments deemed undesirable by the community. A proper sampling strategy design is thus required. A small number of nodes placed in carefully selected farms may produce representative data over an area of interest. The communal information needs and distribution of farms can be taken into account. Instead of a fixated, 24/7 WSN set-up, a mobile set-up within a scatter of farms with agro-climatic similarity may also optimally generate as much data as needed.

Soil texture, topography, weather, vegetation cover, and farm management practices all affect the spatiotemporal variability of soil moisture and temperature. These parameters also vary among different agroecological zones (AEZs) while they tend to be more similar within. In this work, AEZ is, thus, used as a first-level criterion for sample selections. It is used to cluster the study area into three zones that allow us to strategically select sample villages where representative data can be acquired while reducing implementation costs. The three zones are Dega, W. Dega, and Kolla. Within each zone, a random sampling based on sowed crop type and topographic aspect is used to deploy sensors and establish the IoT-WSN network.

Vegetation cover, specifically large trees, poses a challenge in establishing reliable WSN communications. Piles of crop residue and harvested crops may also block the line of sight (LoS) between devices, causing data loss. Placement regimes must minimize such (risk of) hindrance. Nodes and sensor devices must be rugged and withstand environmental impact and be able to run for longer periods. They must remain accessible for maintenance and battery replacement and be physically secure to prevent loss or damage. Farmers often hesitate on innovations in their plots, thus a WSN set-up needs to be non-intrusive and shall not negatively impact routine farming tasks. Thus, nodes are shielded with weather-resistant covers while discussions with farmers aim to create awareness of technology and purpose.

**Infrastructural and logistical considerations** Smallholder farms often suffer from detrimental conditions: their remoteness causes weak communications, and problematic transport and education infrastructure. Complicated access to farms means data is hard to collect and maintenance is hard to sustain. An IoT-WSN must therefore run autonomously with remote monitoring and fault detection functionality. It needs to operate efficiently with its resources, utilize alternative power and communication infrastructure smartly, and with reasonable failure handling. IoT-WSN hardware shall be available in local markets at a reasonable cost and must be transportable to the field. Technology with advanced, complex, or inaccessible components is just an experiment and not a lasting solution to the problems that farmers face. In our work, nodes constitute Arduino boards and micro-controllers, which are easily programmable and also available in close markets. The backend system is configured to identify and indicates failed devices while allowing continuous data view.

**Technical considerations** Hard- and software components of the IoT-WSN shall be based on open and reusable standards. It should allow scalability, maintainability, and transferability with a minimal learning curve. Locally-trained semi-literate citizens shall be able to run, control and maintain the system. Nodes need to be reliable and robust with components that fit into the deployment environment. The choice of network topology, data transmission range, signal interference resistance, and radio frequency are all critical parameters to consider to ensure a reliable and efficient WSN setup.

We identified the Long Range Wide Area Network (LoRaWAN) WSN communication protocol to suit these requirements. The wide spatial coverage and minimal power consumption properties of LoRaWAN are actually what inspired this work. With distances of 10 kms or more, a few nodes suffice to collect reasonable amounts of data in a farm field, cost-effectively. LoRaWAN is an open standard specified by the Long Range (LoRa) alliance. The fact that LoRaWAN runs on the free Industrial, Scientific, and Medical (ISM) spectrum also guarantees real-time in-situ soil monitoring regardless of the network coverage available in smallholder farms. Its ease of implementation and simple configuration make it suitable for communities in which technical skills are scarce [11, 12, 13]. Due to electric power limitations and the absence of strong solar power during the major crop season, nodes must use locally available AA batteries, run longer and provide data without interrupts.

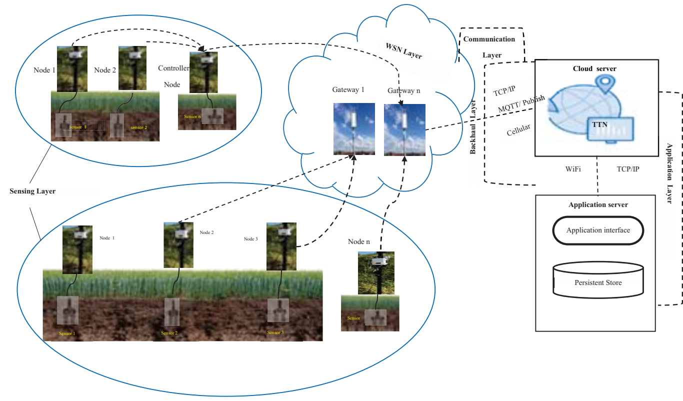


Fig. 2. A WSN-IoT farm monitoring system architecture

### C. Proposed architecture

On the above considerations, our work attempts to implement a LoRaWAN WSN-IoT system for soil moisture and soil temperature monitoring in rural Ethiopia. The general architecture of the proposed system is presented in Fig 2.

There are three layers in the proposed architecture: the sensing layer, the communication layer, and the application layer.

**Sensing Layer**. This layer constitutes the hardware used to set up the WSN: sensors, nodes, and gateways. Sensors are devices with the actual perception of the environment. Nodes are controllers that provide power to sensors, collect sensed data, and process and transmit it to a central data hub. Gateways are special nodes with multi-communication capabilities. They serve as a data sink for nodes and transmit the data to the application server when needed. They also communicate control commands coming from the back-end system to nodes.

Using the AEZ clustering, three representative villages of the study area have been selected to distribute sensors over. These are Asgedo, Haroyie, and Kundina Jerjero villages in the AEZs of Woina Dega (cool sub-humid midland), Dega (tepid cold to humid highland) and Kolla (humid lowland). In collaboration with the local agricultural office, a discussion with farmers about the technology was conducted. A total of 50 volunteer farmers were selected for the sensor installation. The area has a bimodal cropping system: Meher, the major cropping season during June–October, and Belg, a short rainy period during February–April. The system is set up to monitor farms over both seasons. Meher is a rainy period with high cloud coverage and inconsistent and weak solar power. Our village selection is, thus, also based on the availability of the electric grid required to power the gateway. Sensors are placed inside non-fallow farm fields and installed in a soil depth of 10 to 50 cm depending on the crop sowed. Table II presents the target crops in the area with their associated depths.

Nodes are connected to sensors through a serial digital interface (SDI) and mounted on a hanger maximum 2 m high above the ground. Gateways are mounted on a stable stand of 10 m or higher and placed near an administrative

TABLE II
MAJOR CROPS SOWED IN DESSIE ZURIA AND KUTABER DISTRICTS AND THEIR ROOT DEPTHS

| District | Crop | Root depth |
|---|---|---|
| Dessie Zuria | Wheat | 30–50 cm |
| | Teff | 20 cm |
| Kutaber | Wheat | 30–50 cm |
| | Fava beans | 10–30 cm |
| | Teff | 20 cm |

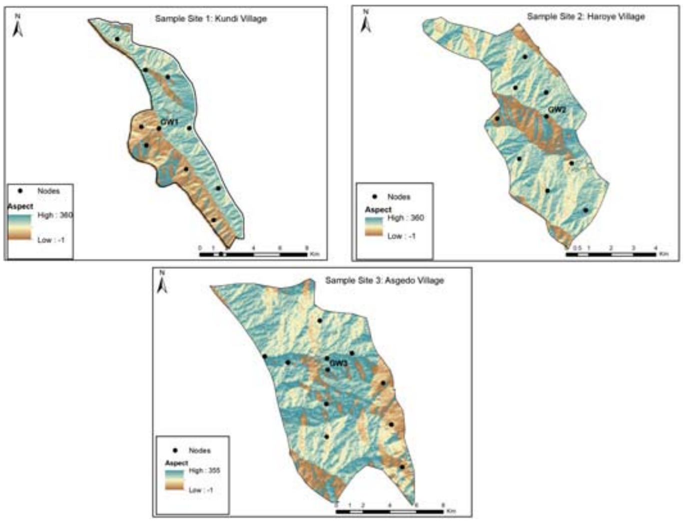


Fig. 3. WSN set up and node distribution over our sample sites

office for direct power supply and safety. Node placement and antenna height are paid special attention to in sensor placement to minimize interference and data loss. Specifically, the topography aspect is used as a criterion to determine node placements within each sample site. The overall distribution of sensors and the WSN setup is shown in Fig 3. All nodes are geo-coded with vertical position using a handheld Garmin etrex 30x GPS device with a horizontal accuracy of 5 m.

**Communication layer**. The communication layer constitutes the WSN and the backhaul layer. A multi-hop star topology with a two-tier layout is envisaged, as shown in Fig 4. A clear sight of communication between the gateway and nodes is aimed at avoiding too much signal blockage. Nodes close to a gateway and with a clear line of sight (LoS) can establish direct communication while those found furthest use controller nodes to reach the gateway. Controller nodes are nodes with the additional functionality of receiving data from nearby nodes and transmit to the gateway by aggregating all the data. A geometric random graph model proposed in [14] is used to determine the maximum distance between nodes and gateway, and we found it to be about 7 kms. Controller nodes are set in a zone only if the distance exceeds this threshold. Such short distance also enables nodes to use power efficiently. Three LoRaWAN gateways, one per zone, are set up and they can support hundreds of nodes.

The backhaul communication facilitates interactions be-

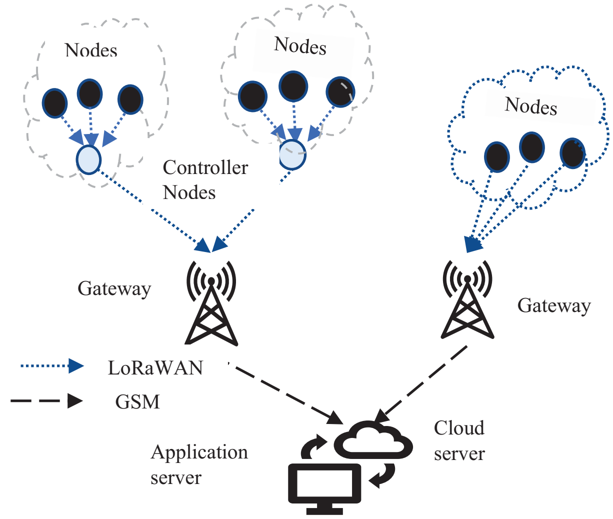


Fig. 4. Logical IoT-WSN layout design

tween the gateway and back-end systems. Gateway to cloud server communication is established with a TCP/IP protocol using cellular communication as this is the only reliable wireless connection available in the area. The Things Network (TTN), an open cloud platform, is used as a cloud server and it allows registration and virtual monitoring of devices. A WiFi protocol handles the interaction between a cloud server and a private application server. Over this communication, the TTN server is configured to transfer the sensor data into a local PostgreSQL database system.

**Application layer**. The business model of our system is defined in this layer. A local database system is configured to receive soil moisture and temperature data from the TTN through publish-subscribe interaction. In this mode, the application server subscribes to the sensed data of nodes and the TTN pushes the data as it arrives. Moreover, the Grafana web dashboard is configured as our data visualization platform for active skimming and monitoring of the incoming data, which can be shared with any third party through a web address.

## D. Instrumentation

Decagon 5TM sensors with 5 m cable length, custom-made LoRa nodes from SODAQ, and a Lorank8 module from IDEETRON are used to set up the IoT-WSN. Sensors measure the volumetric soil water content (VWC in $mm^3$) and soil temperature (in $^\circ C$). The LoRa node has an RN2483 Microchip transceiver (Tx) with an onboard LoRaWAN protocol stack to connect to the gateway. The microchip is embedded in an Arduino board and is programmed to listen to the sensor every 15 minutes. Nodes operate on a power supply voltage of 2 to 3.6 V and 2 AA batteries with 1.5 V each. Nodes are shielded with waterproof plastic cases to withstand environmental effects. Nodes have one internal antenna in our set-up to avoid attention and possible vandalism. The gateway has an omnidirectional external antenna and operates on the ISM 868 MHz frequency. The gateway also comes

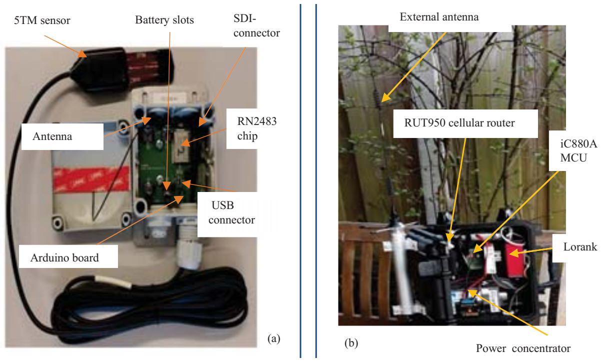


Fig. 5. (a) Sensor connected node with components, cased; (b) LoRaWAN gateway and its components, cased

Fig. 6. IoT-WSN collected soil moisture and temperature data on Grafana web dashboard

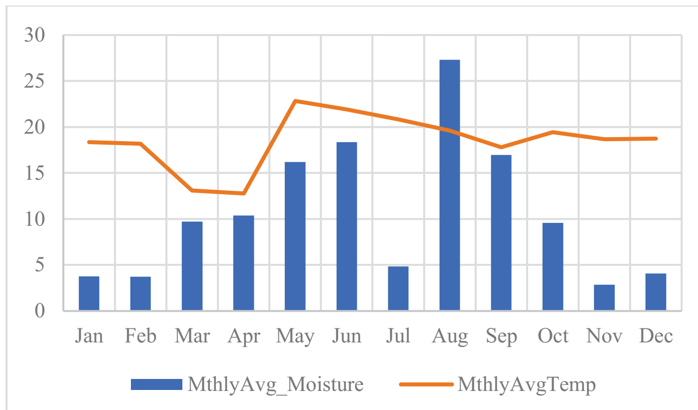


Fig. 7. Sensor collected monthly mean soil moisture and soil temperature readings

with a multi-channel high-performance concentrator module, WiMOD iC880A, which enables the gateway to receive multiple LoRa packets over multiple channels and spreading factors. The gateway runs on a maximum power supply of 5.5 V and a direct electric grid (DC) with a backup rechargeable battery in use. The battery takes over the DC during power interrupts which allows the gateway to run for up to four hours. This has reduced data loss amidst frequent power interruptions in the study area. The gateway also comes with a RUT950 cellular router to establish cloud communication using a local 3G sim card. The gateway and all its components are sealed in a hard plastic case that has mounting connectors. Fig 5 shows devices used in this work.

### *E. Experience to date*

A total of 26 sensors and nodes were distributed over the 14, 17, and 8 $km^2$ of farmlands of the sampled villages. Sensors were tested and calibrated before deployment using manufacturer instructions. Nodes were deployed in an incremental and iterative fashion. Data transmission is set for every 15 minutes with read redundancy and power-saving trade-offs. The IoT-WSN was set up in October 2019 and data collection is still ongoing but has come with significant and frequent disruptions due to unforeseen circumstances. Social conflict in the country and specifically around the study area caused long power and communication disruptions that significantly affected the data collection process. Some devices were broken or stolen, as a result of the conflict. Specifically, the war in the area disrupted our set-up for more than a year starting in July 2021. During the 2019 to 2021 period, a dataset of about 11 Mb sizes was collected.

AA batteries support nodes reliably for three to four months, needing replacement afterward. We also gather parameters that indicate the quality of the signal: received signal strength index (RSSI) and signal-to-noise ratio (SNR). The in-situ data is transmitted to the TTN where a web-based Grafana dashboard is integrated to visualize data. Figs. 6 and 7 show a screenshot taken from the Grafana dashboard displaying readings of a sensor, and a graph of aggregated monthly soil moisture and temperature data of all sensors.

The data collection process was hampered for both technical and physical reasons, in addition to those of the war. The power and 3G communication instability, nodes damaged by cattle grazing in the fields, or passing by children were the dominant reasons.

## III. Discussion and Conclusions

In this paper, we present an IoT-WSN system for monitoring farms in rural areas. The LoRaWAN protocol covers a wider area with minimal power consumption and exhibits strong resistance to noise interference. About 5,000 farm plots exist within the sample sites. Only 50 plots were selected due to resource limitations. The number of nodes distributed to each sample site depends on the total farmland area. Accordingly, 11, 8, and 7 nodes were set up in Haroye, Kundi, and Asgedo sites respectively, with only one node per field. Some 22, 13, and 12 plots in these sites were used for the installation. Thus, nodes rotated in different fields within the same site to cover all 50 farm plots. For Asgedo and Haroye sites, the WSN was set up in October–November 2019, while for the Kundi site, this was done in March 2020. The metadata of node placement is presented in Table III below.

TABLE III
GENERAL INFORMATION ABOUT THE WSN SET-UP

| NodeId | Latitude | Longitude | Elevation (m) | Height (m) | Installation Depth (cm) | Installation Date | Planted Crop | Village |
|---|---|---|---|---|---|---|---|---|
| GW1 | 11.357828 | 39.455527 | 2072 | 15 | 0 | 11/4/2020 | | Kundi |
| GW2 | 11.26013 | 39.516609 | 2808 | 20 | 0 | 21/11/2019 | | Haroye |
| GW3 | 11.07511 | 39.51395 | 2600 | 27 | 0 | 18/9/2019 | | Asgedo |
| SOM03 | 11.07733 | 39.51587 | 2786 | 2.5 | 15 | 18/9/2019 | Teff | Asgedo |
| SOM06 | 11.35909 | 39.443486 | 2883 | 1 | 20 | 21/11/2019 | Teff | Haroye |
| SOM07 | 11.258168 | 39.51645 | 2821 | 1 | 15 | 21/11/2019 | Fava Bean | Haroye |
| SOM09 | 11.357612 | 39.454995 | 2078 | 1 | 15 | 15/4/2020 | Teff | kundi |
| SOM10 | 11.08015 | 39.511484 | 2470 | 2 | 40 | 18/9/2019 | Wheat | Asgedo |
| SOM12 | 10.86803 | 39.395341 | 2592 | 2 | 25 | 15/4/2020 | Maize | kundi |
| SOM13 | 11.07452 | 39.51363 | 2599 | 2 | 20 | 20/9/2019 | wheat | Asgedo |
| SOM14 | 10.88494 | 39.400048 | 2545 | 1.6 | 20 | 18/9/2019 | Teff | Asgedo |
| SOM15 | 11.07458 | 39.51349 | 2598 | 2 | 30 | 18/9/2019 | Wheat | Asgedo |
| SOM16 | 10.86839 | 39.395808 | 2519 | 2 | 20 | 18/9/2019 | Fava Bean | Haroye |
| SOM17 | 11.25911 | 39.516845 | 2870 | 2 | 30 | 11/4/2020 | Fava Bean | Haroye |
| SOM18 | 11.25904 | 39.516955 | 2869 | 2 | 30 | 21/11/2019 | Barley | Haroye |
| SOM19 | 11.258665 | 39.516561 | 2748 | 1.5 | 15 | 21/11/2019 | Barley | Haroye |
| SOM20 | 11.3581 | 39.455564 | 2029 | 1.9 | 10 | 15/4/2020 | Maize | kundi |
| SOM21 | 11.25903 | 39.517028 | 2886 | 2 | 20 | 21/11/2019 | Barley | Haroye |
| SOM22 | 11.08015 | 39.511484 | 2657 | 2 | 18 | 18/9/2019 | Teff | Asgedo |
| SOM23 | 11.07923 | 39.514321 | 2586 | 3 | 15 | 18/9/2019 | Fava Bean | Asgedo |
| SOM26 | 11.10611 | 39.756303 | 2456 | 1.5 | 20 | 21/11/2019 | Barley | Haroye |
| SOM28 | 11.358036 | 39.455289 | 2065 | 2 | 20 | 15/4/2020 | Teff | Kundi |
| SOM31 | 11.25741 | 39.516293 | 2789 | 2.3 | 30 | 21/11/2019 | wheat | Haroye |
| SOM33 | 11.26056 | 39.513889 | 2870 | 2 | 30 | 15/4/2020 | wheat | Haroye |
| SOM38 | 11.07866 | 39.513697 | 2450 | 1.5 | 20 | 21/11/2019 | Teff | Haroye |
| SOM39 | 11.35743 | 39.51581 | 2084 | 1.7 | 30 | 18/9/2019 | wheat | Kundi |
| SOM41 | 11.35436 | 39.464424 | 2132 | 2 | 20 | 15/4/2020 | Wheat | Kundi |
| SOM50 | 11.35741 | 39.516293 | 2120 | 1.8 | 20 | 15/4/2020 | Teff | Kundi |
| SOM52 | 11.35353 | 39.466124 | 2140 | 1.4 | 20 | 15/4/2020 | Teff | Kundi |

The dynamic nature of soil moisture requires rigorous data validation against well-established readings. Sensor data validation was conducted only once due to budget constraints. In-situ weather stations should have been used instead but none exist in the area at present. To fill this gap, an automated weather station (ATMOS) is set in one of the districts along with the WSN setup. This also helps to establish an all-around agrometeorological data infrastructure in the area. Design considerations were made appropriate to smallholder farms before the actualization of the system. However, the considerations made were not exhaustive and this has caused the set-up to suffer significant data loss. Redundant data storage options need to be considered where either controller nodes or gateways keep data internally until stable communication to a back-end system is secured or data is manually retrieved periodically.

Given the variability of soil moisture data, the currently collected data is not enough to base further analysis on. it is useful to validate and complement remotely sensed soil moisture data. Such is a significant contribution as this data does not exist, even at the country level, in Ethiopia. Right now, nodes are maintained and the WSN-IoT has been set up afresh. We plan to collect as much data as possible until October 2023, until the end of the Meher farming season. The data, together with other remotely sensed and generated data, will be used to build an agriculture knowledge base to support in-season farm decisions.

We believe such a WSN-IoT system generates trustworthy local data and could assist sustainable and productive farming through a better understanding of the local context of farm production and productivity parameters.

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