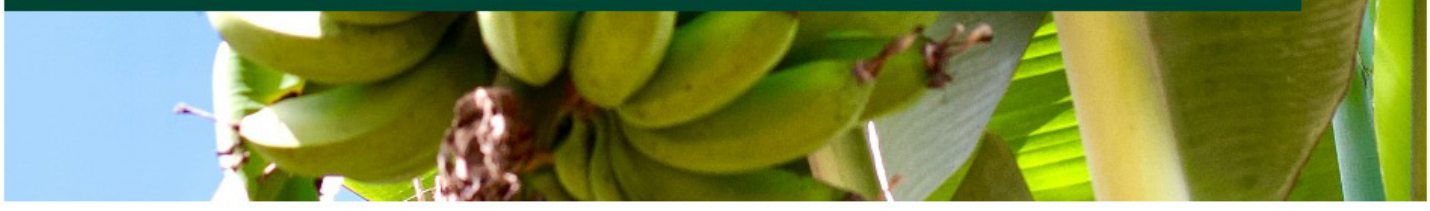
50x2030
DATA-SMART AGRICULTURE

TECHNICAL NOTE ON

USING IN SITU SENSORS FOR WEATHER MONITORING AND DATA COLLECTION

Practical Guidance Based on Methodological Research in Uganda

KOREA GREEN GROWTH TRUST FUND



Acknowledgments

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The 50x2030 Initiative to Close the Agricultural Data Gap is a multi-agency effort aimed at supporting 50 low- and lower-middle-income countries to produce fundamental agricultural and rural data through the use of integrated agricultural and rural surveys. For more on the Initiative, please visit www.50x2030.org.

1. Background and Motivation

Agriculture is the backbone of Uganda's economy, with most of the population relying on farming as a primary source of livelihood. As in many sub-Saharan African countries, Uganda's agricultural sector faces growing challenges from climate change, including increasingly erratic rainfall patterns and more frequent extreme weather events. These stresses directly affect agricultural productivity and heighten risks for smallholder farmers. Effective adaptation and risk management depend on access to reliable, localized weather and climate information to support decisions related to planting, irrigation, and harvesting.

However, the availability of accurate, high-resolution weather data in Uganda remains limited. The Department of Meteorological Services (DMS), under the Ministry of Water and Environment, is responsible for maintaining the national meteorological observation network and disseminating weather and climate information. DMS operates 87 automatic weather stations (AWS) that transmit data to a central server in Kampala. Despite this infrastructure, coverage remains sparse, particularly in rural areas where most agricultural activity takes place. Existing research estimates that an optimal rain gauge network for Uganda would require approximately 1,057 stations (Isabirye, 2017), well above current levels. In addition, most existing AWS do not transmit to the WMO Global Basic Observing Network (GBON) due to unmet technical and reporting standards (World Meteorological Organization, 2024). The network comprises equipment from multiple manufacturers, creating challenges for standardization and maintenance, although DMS has identified the ADCON system as its preferred standard. A 2023 census of weather stations conducted by DMS in collaboration with the World Bank highlights uneven national coverage, with 15 percent of districts entirely unmonitored and fewer than half of the surveyed stations fully operational.

The limited availability of localized weather observations has multiple compounding consequences. From an operational and farmer-facing perspective, sparse local observations undermine the accuracy of weather forecasts and early warning systems. This constrains farmers' ability to anticipate, plan for, and respond to extreme weather events such as droughts and floods, weakening climate-informed decision-making and directly affecting agricultural productivity, risk management, and household livelihoods. From a research and analytical perspective, weather variables used in survey-linked agricultural analyses are frequently derived from satellite-based products that rely on sparse ground-station networks for calibration and validation. Limited in situ observations restrict effective ground-truthing, increasing the risk of measurement error in key weather inputs. When such data are used in yield and production models, measurement error can bias estimated relationships, reverse coefficient signs, inflate statistical significance, and distort program diagnostics, impact evaluation, and targeting decisions.

Within this context, low-cost[1], in situ weather sensing technologies offer a potential pathway to address observational gaps in data-sparse regions by enabling denser monitoring networks at relatively low cost. However, despite increasing availability, the performance and data quality of these technologies remain insufficiently documented, particularly under the local environmental and institutional conditions in which they would be deployed. Rigorous testing and validation are therefore necessary to assess their suitability for both operational and research applications.

This technical note provides practical guidance on the collection of ground-based weather data using low-cost, in situ sensors, and offers insights into their performance and accuracy in local environments. These insights are based on comparisons with professional-grade reference technologies and remote sensing-based data sources traditionally used in agricultural and weather forecasting analyses. The note is intended for survey practitioners and researchers seeking to enhance household- and farm-level datasets with accurate, high-frequency weather measurements, as well as for project designers and implementers working in areas such as precision agriculture, climate risk assessment, and environmental monitoring.

The analysis draws on implementation experience and lessons from the Uganda Climate, Land Area, and Soil Study (CLASS) and focuses on the deployment and testing of a specific low-cost weather sensor, the Arable Mark 2. Accordingly, the methodological recommendations and data quality considerations presented are tailored to the characteristics and observed performance of this sensor. At the same time, the study is intended as an initial proof of concept for integrating low-cost, in situ weather sensors with household and agricultural surveys. While the findings indicate promising applications, they are exploratory in nature and are intended to inform future piloting, refinement, and scaling across a broader range of weather measurement technologies and implementation contexts.

Following an overview of the Uganda Climate, Land Area, and Soil Study (CLASS), the note presents findings from the evaluation of the Arable Mark 2 sensor, covering measurement accuracy relative to professional meteorological stations and remote sensing–based rainfall products, as well as operational performance and data reliability over the deployment period. It then provides technical guidance on planning and implementing sensor deployment, including site selection and installation, and data transmission and retrieval. A value proposition section examines the cost structure of in situ sensor networks and situates low-cost sensors within the broader landscape of available weather data sources. The note concludes with lessons learned from the Uganda CLASS experience and practical recommendations for teams considering similar deployments.

2. Overview of the Uganda CLASS and its Climate Component

The Uganda Climate, Land Area, and Soil Study (CLASS) was implemented by the World Bank's Living Standards Measurement Study (LSMS) under the 50x2030 Initiative, in collaboration with and with financial support from the World Bank's Agriculture and Food Global Practice. The study validates

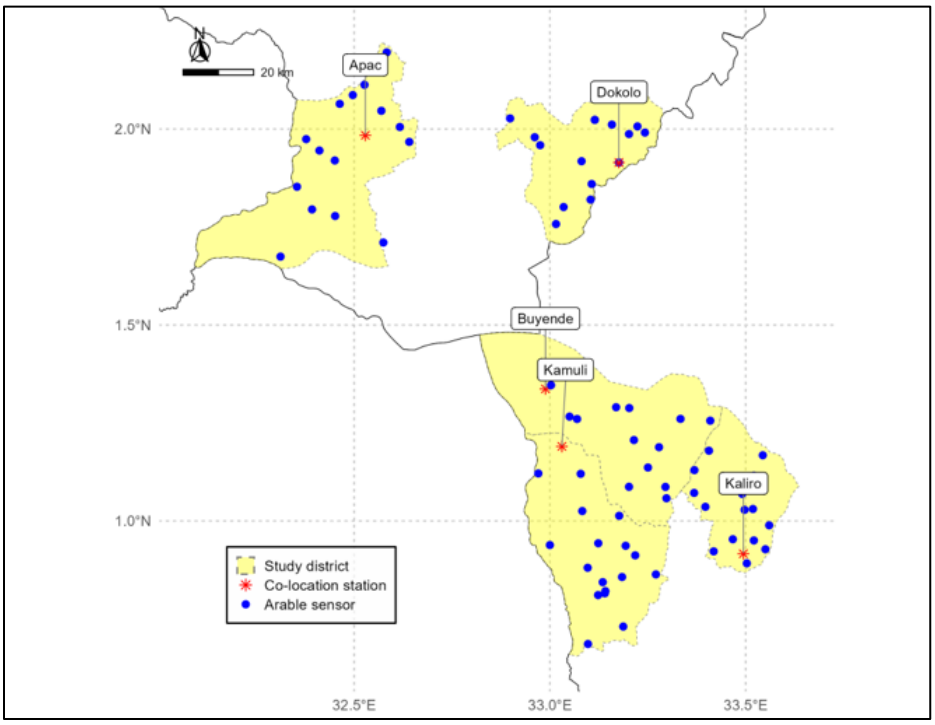
[1] Throughout this note, "low-cost" refers to meteorological instruments that are substantially less expensive than conventional professional-grade weather stations, while satisfying the functional criteria defined by the World Meteorological Organization (2018) for low-cost automatic weather stations.

and compares innovative data collection methods for agricultural household surveys across three domains: climate and weather, land area measurement, and soil health. The climate component focused on testing low-cost weather-sensing technologies, evaluating their measurement accuracy relative to professional systems, assessing overall performance, and examining the operational feasibility of integrating the collection of these data into survey workflows. The selected technology was the Arable Mark 2 weather sensor, chosen for its combination of scientific-grade accuracy and moderate cost (see Section 3 for details).

This activity was aligned with and supported the Uganda Climate Smart Agriculture Transformation Project (CSATP), which aims to increase weather-station density and strengthen local agro-meteorological information systems and advisory services, with the Uganda Department of Meteorological Services (DMS) serving as the implementing agency for this component. The DMS supported implementation of the climate component of the Uganda CLASS and was responsible for the installation and maintenance of the weather sensors, including facilitating engagement and buy-in from local authorities. This collaboration among the DMS, local authorities, and the World Bank sought to ensure that study findings address technical requirements, community needs, and research priorities. The DMS intended to use the study's findings to inform decisions on potential sensor procurement and adoption, and to provide evidence in support of additional investment to expand the observation network using lower-cost technologies relative to professional-grade stations. By providing accurate, real-time, localized weather data, these lower-cost devices have the potential to improve forecasting and, in turn, support better agricultural decision-making and enhance local communities' capacity to adapt to changing environmental conditions, which are key objectives of the Uganda CSATP.

In August 2023, a total of 80 Arable Mark 2 devices were deployed across five districts in Eastern and Northern Uganda: Buyende, Kamuli, Kaliro, Apac, and Dokolo. Five devices were co-located with existing professional-grade ADCON weather stations — the standard technology recommended by the DMS — enabling direct comparison between the low-cost sensors and reference DMS-operated systems. The remaining 75 devices were installed on the farms of designated model farmers within enumeration areas (EAs) where an agricultural survey of 900 maize-producing households was conducted during September 2023 – March 2024. In each district, 15 EAs were randomly selected for inclusion, with one device deployed per EA. While the selection of EAs was randomized, the specific installation locations within each EA were determined based on technical and operational feasibility. Technical site-selection criteria included unobstructed exposure to atmospheric conditions, minimal environmental interference, and reliable network connectivity. Operational considerations included farmers' willingness to host the device and the availability of an on-site caretaker responsible for safeguarding and routinely monitoring the equipment following installation, supported by a small monthly compensation. Figure 1 illustrates the spatial distribution of the deployed Arable Mark 2 devices and the locations of the co-location reference stations.

Figure 1. Spatial distribution of Arable devices and co-location stations across Uganda CLASS districts.



Source: Paolantonio et al. (*forthcoming*).

3. Performance Assessment of In Situ Weather Sensors

This section summarizes key findings from the Uganda Climate, Land Area, and Soil Study (CLASS) concerning the performance of the Arable Mark 2 sensor, with a focus on rainfall measurement. Rainfall is central to rainfed farming systems in Uganda and plays a critical role in shaping agricultural productivity, climate risk, and policy responses. It examines both measurement accuracy — assessed through comparisons with professional-grade weather stations[2] and remote sensing-based rainfall products — and operational performance, including data completeness, sensor reliability, and system failures observed during the deployment period. The findings presented here draw heavily on Paolantonio et al. *(forthcoming)*, which provides a detailed validation of the Arable Mark 2 sensor and examines how differences in rainfall data sources affect agricultural inference for maize-producing households in the study districts.

Three key takeaways emerge from this evidence:

[2] While Arable Mark 2 devices are validated against research-grade reference instruments across a global network of co-location sites spanning multiple climatic zones in North America, Europe, and Australia (for more information see: https://www.arable.com/blog/how-arable-achieves-world-class-accuracy/), this manufacturer testing is not typically conducted under the diverse real-world conditions found in low-income country settings. The Uganda CLASS provides an independent field validation of these claims using national meteorological service benchmarks as the reference standard.

1. Arable Mark 2 rainfall measurements closely match professional-grade weather stations across multiple performance metrics and temporal scales, supporting their use as reliable field-level data sources.
2. Remote sensing-based rainfall products differ systematically from in situ measurements, particularly at daily resolution and for measures of rainfall variability and extremes.
3. These measurement differences materially affect conclusions about agricultural outcomes, with remote sensing-based products sometimes producing strong but unstable yield–rainfall relationships that are not supported when using field-level measurements.

Together, these findings underscore that the choice of rainfall data sources can strongly shape both the characterization of local climate conditions and the interpretation of weather–agriculture relationships.

3.1 Measurement Accuracy of Arable Mark 2

The comparative evaluation benchmarks Arable Mark 2 rainfall measurements against professional ADCON stations operated by the DMS, which are treated as the ground truth. The analysis spans 1 September 2023 to 30 June 2024 and assesses accuracy across three temporal scales — daily, dekadal (10-day), and monthly — to capture different facets of rainfall variability relevant to agriculture. Daily data resolve short-term events such as storms and dry spells; dekadal aggregation attenuates day-to-day noise while preserving intraseasonal patterns, and monthly totals provide a seasonal overview of cumulative rainfall. Evaluating performance at multiple aggregation levels helps reveal or, in some cases, mask differences in measurement. In parallel, the study compares Arable Mark 2 with three widely used remote sensing-based (RS) rainfall products — ARC2, CHIRPS 2.0, and TAMSAT — which differ in spatial resolution and production methodology.

Overall, evidence from the Uganda CLASS indicates a high level of agreement between Arable Mark 2 and professional ADCON stations across rainfall magnitudes and variability. At the same time, comparisons with RS rainfall products point to a clear takeaway: the choice of rainfall measurement approach strongly shapes the picture of rainfall that is observed, particularly at fine temporal scales and for measures of variability and extremes.

Performance of Arable Relative to Professional Benchmarks

Figure 2 compares the accuracy of the Arable Mark 2 sensor against the three RS products, showing correlation coefficients (Panel A) and relative root mean square error (Panel B) at daily, dekadal, and monthly resolutions. The Arable sensor achieves strong agreement with professional-grade ADCON stations across all three temporal scales. Correlation coefficients exceed 0.8 at the daily level and climb above 0.9 at dekadal and monthly resolutions, indicating close alignment in both the timing and cumulative accumulation of rainfall. Relative RMSE values are low and stable across aggregation levels, reflecting small deviations from ADCON measurements when expressed relative to observed rainfall magnitudes. These performance levels are consistent across the four co-location sites in the study area.

Figure 3 provides a more targeted view of sensor performance where it matters most for agricultural risk analysis: the accurate detection of high-intensity rainfall events. The stacked bar format shows, for each data source, what share of observed heavy (20–39.9 mm/day) and violent (≥40 mm/day)

rainfall days were correctly identified relative to the ADCON benchmark, and what share were missed. The Arable sensor correctly detected approximately 56 percent of heavy rainfall events and over 50 percent of violent events, a substantially higher detection rate than any of the RS products evaluated.

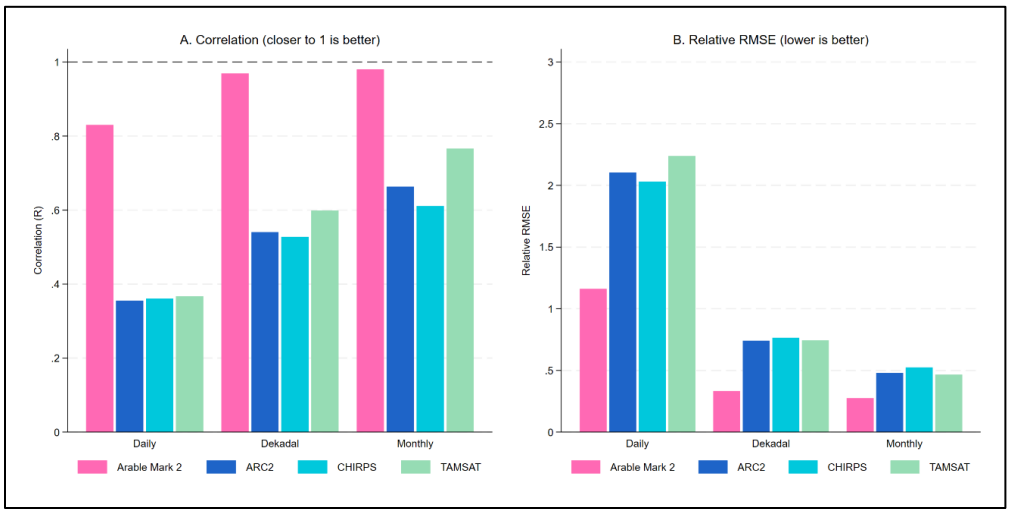
Comparison with Remote Sensing–Based Rainfall Products

As shown in Figure 2, all three RS products — ARC2, CHIRPS, and TAMSAT — exhibit systematically lower correlation and higher rRMSE values than Arable at all temporal resolutions. The performance gap is most pronounced at the daily scale, which is consistent with the well-documented tendency of satellite products to attenuate day-to-day rainfall variability and to misalign the timing of events at the field level. This limitation becomes particularly consequential when satellite products are used as inputs to plot-level agricultural analysis.

The contrast is even starker for extreme-event detection (Figure 3). Detection rates across the three RS products ranged from only 5 to 14 percent for heavy rainfall events and fell to zero for violent events, meaning that not a single violent rainfall episode was captured by any satellite product across the entire monitoring period. This is not a marginal difference: it represents a near-complete failure to detect the category of rainfall most relevant to crop damage, waterlogging, and acute drought stress. For analysis that focuses on agricultural shocks, flood exposure, or the design of index insurance triggers, this systematic underrepresentation of extremes can produce misleading risk assessments and misdirect interventions.

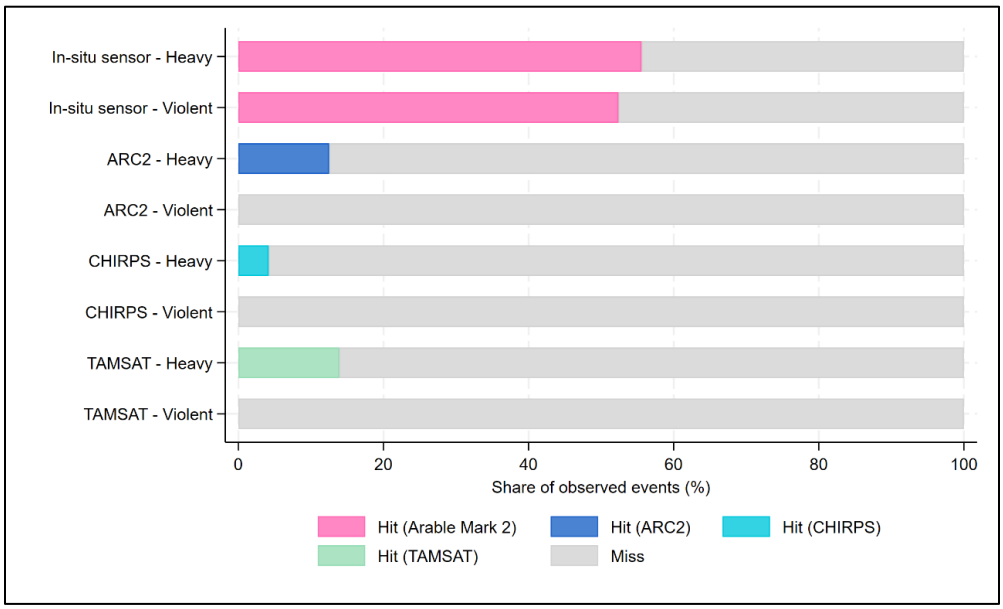
These discrepancies reflect fundamental differences in measurement scale and data construction. Whereas Arable records rainfall at a point location in the field, products such as ARC2, CHIRPS, and TAMSAT represent spatial averages over grid cells of roughly 4 to 11 kilometers. Localized convective rainfall events, which are common in the Ugandan context, may therefore be partially or fully smoothed out in RS estimates. Satellite retrieval uncertainty, limited gauge-based calibration, and temporal downscaling procedures compound this problem by blurring the timing and intensity of individual events. As a result, and as clearly visible in Figures 2 and 3, RS products tend to overstate the frequency of light rainfall days, underrepresent heavier events, and dampen day-to-day variability, limitations that become increasingly consequential as the focus of analysis shifts from seasonal totals to intraseasonal patterns and extremes.

Figure 2. Rainfall measurement performance by data source and temporal aggregation.



The figure shows correlation coefficients (Panel A) and relative root mean square error (Panel B) for the Arable Mark 2 in situ sensor and three satellite-based gridded products (ARC2, CHIRPS, TAMSAT), computed against ADCON stations benchmarks at daily, dekadal (10-day), and monthly resolutions over the period 1 September 2023 – 30 June 2024. Higher correlation and lower rRMSE indicate closer agreement with the benchmark. Values are aggregated across four co-location sites in Uganda. Produced based on Figure 4 in Paolantonio et al., 2026 (*forthcoming*).

Figure 3. Detection of heavy and violent rainfall events by data source.



The figure shows the share of observed heavy (20–39.9 mm/day) and violent (≥40 mm/day) rainfall events correctly detected (hits, coloured segment) or missed (grey segment) by the Arble Mark 2 in situ sensor and three satellite-based gridded products (ARC2, CHIRPS, TAMSAT), over the period 1 September 2023 – 30 June 2024. A hit is recorded when both the evaluated product and ADCON station benchmark agree that rainfall falls within the same intensity category on a given day. Values are aggregated across four co-location sites in Uganda. Produced based on Figure 5 in Paolantonio et al., 2026 (*forthcoming*).

When extending the comparison beyond co-located validation sites to the full network of 80 Arable deployment locations, the contrast between Arable and RS rainfall products becomes even clearer,

as shown in Table 1. Network-wide indicator comparisons show that while Arable's total seasonal rainfall is broadly consistent with ARC2 and CHIRPS, its point-scale measurements capture substantially greater day-to-day variability. Relative to RS products, Arable records fewer spurious light-rain days, longer and more frequent dry spells, and a higher incidence of intense rainfall events. These differences are statistically significant across a wide range of derived indicators, including measures of rainfall variance, the length and frequency of dry spells, and the occurrence of heavy and violent rainfall events. In effect, Arable preserves intraseasonal structure and extremes that are systematically smoothed in RS rainfall products.

For implementers, the implication is pragmatic: denser networks enabled by lower-cost in situ sensors such as Arable have the potential to improve daily rainfall intelligence and the detection of agriculturally relevant extremes, provided that other considerations — including costs, operational feasibility, and maintenance requirements — are carefully assessed. Satellite datasets would continue to serve as valuable complements for broader spatial coverage and for analyses conducted at coarser temporal resolutions.

Table 1. Two-sample t-test between Arable and RS rainfall products for derived rainfall indicators across 80 sites.

	Arable	**ARC2**			**CHIRPS**			**TAMSAT**		
	Mean	Mean	Diff.	p-value	Mean	Diff.	p-value	Mean	Diff.	p-value
Total seasonal rainfall	1120.15	1159.55	-39.40	0.13	1125.56	-5.41	0.86	1276.63	-156.48	0.000
Mean of daily rainfall	3.70	3.83	-0.13	0.13	3.72	-0.02	0.86	4.21	-0.52	0.000
Number of days with rain	102.20	146.64	-44.44	0.00	147.48	-45.28	0.00	123.93	-21.73	0.000
Number of days without rain	158.73	144.80	13.93	0.00	145.69	13.04	0.00	169.51	-10.79	0.000
Variance of daily rainfall	70.04	36.46	33.58	0.00	25.70	44.35	0.00	46.02	24.02	0.000
Coefficient of variation of daily rainfall	2.22	1.58	0.64	0.00	1.37	0.85	0.00	1.61	0.61	0.000
Longest days without 1 mm	16.84	12.45	4.39	0.00	13.26	3.58	0.00	17.40	-0.56	0.592
Longest days without 5 mm	28.60	21.88	6.73	0.00	21.21	7.39	0.00	22.28	6.33	0.000
Number of periods longer than 7 days with <1mm	6.29	5.05	1.24	0.00	5.04	1.25	0.00	5.25	1.04	0.000
Number of periods longer than 7 days with <5mm	10.03	9.16	0.86	0.00	8.39	1.64	0.00	6.79	3.24	0.000
Number of periods longer than 14 days with <1mm	1.45	0.18	1.28	0.00	0.44	1.01	0.00	1.06	0.39	0.044
Number of periods longer than 14 days with <5mm	3.98	2.55	1.43	0.00	2.18	1.80	0.00	1.73	2.25	0.000
Longest days with heavy rain [20,40 mm)	1.71	1.48	0.24	0.00	1.15	0.56	0.00	1.71	0.00	1.000
Longest days with violent rain (>= 40 mm)	0.91	0.09	0.83	0.00	0.00	0.91	0.00	0.09	0.83	0.000
Total number of days with heavy rain [20,40 mm)	13.58	8.93	4.65	0.00	4.14	9.44	0.00	12.14	1.44	0.022
Total number of days with violent rain (>= 40 mm)	3.01	0.10	2.91	0.00	0.00	3.01	0.00	0.14	2.88	0.000

Source: Paolantonio et al. (*forthcoming*).

Implications for Agricultural Productivity Analysis

Differences in rainfall measurement have direct consequences for agricultural inference, as documented in Paolantonio et al. (*forthcoming*). Using plot-level survey data from the Uganda CLASS and an identical set of rainfall indicators, maize yield regressions based on Arable measurements produce consistently small, precisely estimated coefficients that are statistically insignificant across specifications, both with and without controls for input use and household and plot characteristics. For the 2023 second agricultural season, these results suggest that rainfall variation, when measured accurately at the field level, had at most modest marginal effects on maize yields in the study districts. Importantly, this finding is consistent with the specific meteorological conditions of that season, which was unusually wet and spatially widespread — driven by concurrent El Niño

and positive Indian Ocean Dipole conditions — resulting in above-normal rainfall across much of Uganda. When most households experience ample and relatively homogeneous rainfall, cross-sectional variation in both totals and intraseasonal patterns is compressed, reducing the ability of yield–rainfall regressions to detect agronomic effects even when they exist.

In contrast, regressions using rainfall measures derived from RS products more frequently yield larger and occasionally statistically significant coefficients, particularly for indicators capturing rainfall variability, dry spells, and heavy rainfall days. However, these estimates tend to be less stable across specifications and in some cases imply yield responses that are difficult to reconcile with agronomic expectations — for instance, positive yield effects of greater rainfall variability or more frequent dry days. The divergence between Arable- and RS-based results raises the possibility that some of the apparent yield–rainfall relationships identified using RS products may partly reflect measurement noise rather than genuine agronomic signals.

These findings underscore that the choice of rainfall measurement can materially affect conclusions about agricultural productivity and climate sensitivity. When alternative rainfall sources produce different coefficients, different levels of statistical significance, or even different signs on the same indicator, the resulting inference is difficult to interpret and potentially misleading for both research and policy purposes. In environments characterized by highly localized and intermittent rainfall, field-level measurements offer a more reliable basis for inference than satellite-derived alternatives. That said, the practical implication is not that RS products should be set aside, but that their use for plot-level agricultural analysis warrants caution, particularly when significant results are sensitive to specification choice or difficult to reconcile with agronomic priors. Wherever feasible, local sensor data can strengthen inference by providing a basis for validating satellite-based findings and increasing confidence in both null and non-null results.

3.2 Operational Performance and Data Reliability

Deployment of the Arable Mark 2 sensors took place between 10 and 26 August 2023, with devices installed and brought online on a rolling basis across districts. Once activated, sensors recorded field-level weather conditions continuously until decommissioning in July 2025, when the study period concluded following the end of available funding. The discussion below focuses on sensor performance over this active recording period.

During the recording period, Arable devices experienced intermittent operational issues that affected data availability and quality. These consisted primarily of (i) sensor failures, in which specific weather variables were missing or invalid due to sensor malfunction, and (ii) inactive sensor events, in which devices temporarily ceased transmitting primarily due to connectivity issues. Malfunctioning units were replaced, when possible, using available spare devices. At some sites, external antennas were installed to boost network connectivity and reduce transmission interruptions. However, both device replacements and antenna deployments were constrained by limited availability and logistical challenges, further compounded by shipment delays, customs procedures, and the availability of funds to support field missions. As a result, not all failures could be immediately resolved.

Figure 4 traces the cumulative evolution of these disruptions over the recording period. The profiles rise gradually rather than in sharp steps, suggesting that operational issues accumulated steadily

across the deployment rather than clustering around specific episodes. Inactive sensor events — primarily connectivity-related — accrued more rapidly than outright sensor failures, pointing to intermittent, recurrent inactivity as the main source of data loss over the life of the devices.

Figure 5 breaks this down by district, reporting the average number of failures and inactive events per device. Inactive events consistently outnumber sensor-specific failures across all districts, with averages ranging from 3.2 to 8.3 inactive events per device compared to 2.1 to 7.3 failures, and overall means of 5.2 and 4.1 respectively. Spatial variation is considerable: Dokolo recorded the highest incidence of both disruption types, Kaliro the lowest, with Apac, Buyende, and Kamuli falling in between.

Frequency, however, only tells part of the story. Figure 6 reports average event durations, which determine how much data was ultimately lost. Sensor failures persisted for an average of 43.2 days, ranging from 24.4 days in Dokolo to 67.6 days in Kamuli and 56.6 days in Apac. Inactive events lasted slightly longer on average — 50.0 days overall — but with sharper variation across districts: Kaliro and Apac experienced particularly prolonged inactive periods (90.6 and 72.6 days respectively), while Buyende's interruptions averaged just 6.5 days.

Read together, Figures 4–6 show that data availability was shaped by both how often disruptions occurred and how long they lasted, with the two dimensions not always moving in tandem. A district like Dokolo, with frequent but shorter disruptions, may have lost less data overall than one with fewer but more persistent events.

Figure 4. Cumulative sensor failures and inactive events over the recording period (August 2023 – July 2025).

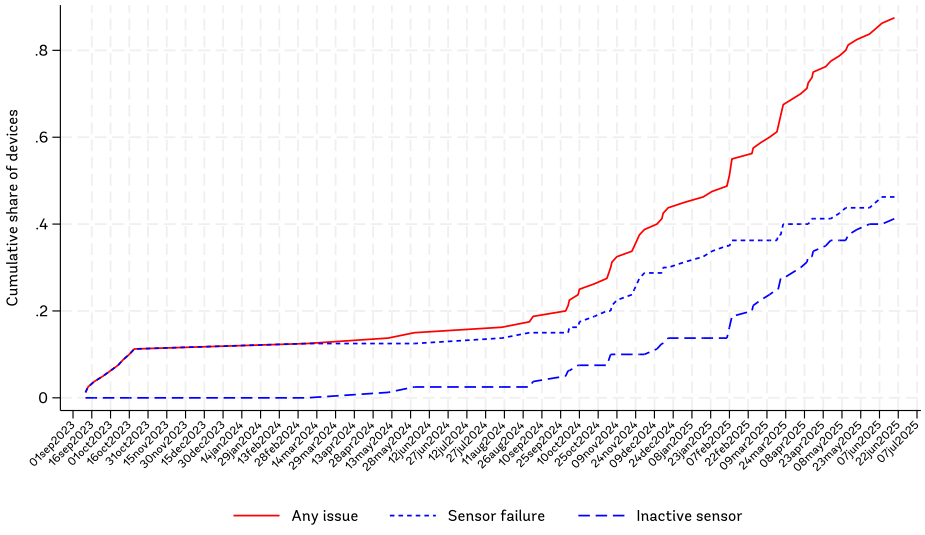


Figure 5. Average number of sensor failures and inactive events per device, by district.

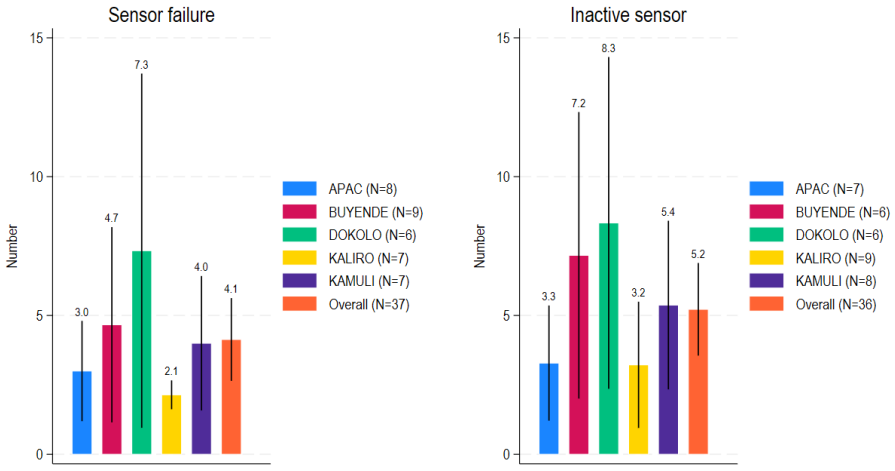
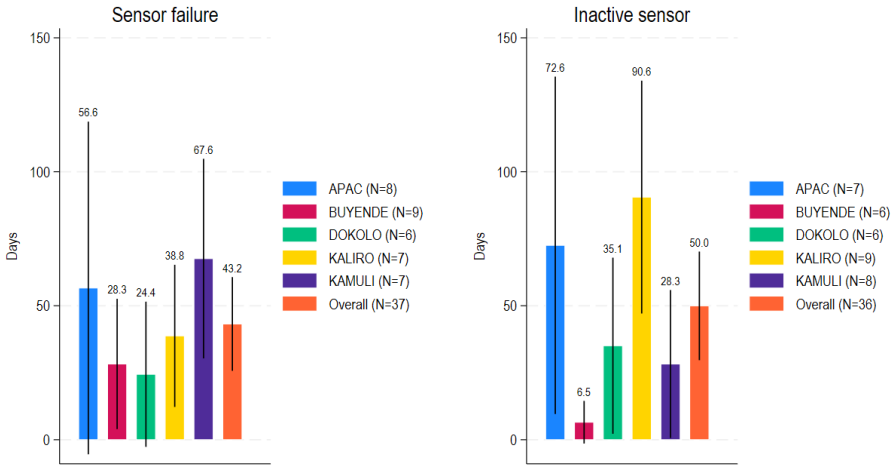


Figure 6. Average duration of sensor failures and inactive events per device, by district.



The observed performance of the Arable Mark 2 sensors highlights several practical considerations for teams planning or managing field-level weather monitoring systems:

- **Expect and plan for intermittent data gaps**. Continuous data availability should not be assumed. Sensor failures and connectivity-related outages are likely over long deployment periods, making it important to plan for non-continuous data streams and to consider appropriate methods for handling missing weather data, including carefully justified imputation strategies.[3]

[3] For examples of possible imputation approaches for rainfall data, see Paolantonio et al. (forthcoming).

- **Connectivity is critical**. Connectivity deserves particular attention at the site selection stage. Temporary device inactivity driven by network issues was a major source of data loss in the Uganda CLASS, and systematic connectivity checks carried out before installation can help reducing such gaps.
- **Account for both frequency and duration of disruptions.** Data reliability depends not only on how often failures occur, but also on how long they persist. Prolonged outages can substantially reduce usable data even when events are infrequent.
- **Monitor performance at the variable level**. Individual sensors can fail while the device continues to transmit, making variable-specific quality control an essential part of the data management routine rather than an optional step.

Field-level weather sensors offer genuine value for localized measurement, but their effective use depends on sustained monitoring, transparent documentation of operational performance, and honest accounting of data gaps in any analysis that follows. It is also worth noting that newer generations of the technology — such as the Arable Mark 3 — are expected to address several of the limitations observed in the Mark 2 devices and may reduce the incidence of both connectivity issues and sensor-level failures in future deployments.

4. Using In Situ Weather Sensors: Arable Mark 2 Example

Recent advances in sensor miniaturization, IoT connectivity, and cloud computing have accelerated the development of a new generation of lower-cost, rapidly deployable in situ weather monitoring technologies. These systems are increasingly used to complement or densify conventional meteorological networks, particularly in data-scarce regions. Unlike traditional automatic weather stations, which often require substantial upfront capital investment, specialized installation, and ongoing technical maintenance, newer platforms are typically self-contained, solar-powered, and designed for simplified field deployment with remote data transmission. Some systems additionally integrate forecasting functions and agronomic advisory capabilities.

The World Meteorological Organization (2018) characterizes “low-cost” automatic weather stations as systems with an affordable unit cost — typically below USD 5,000 — provision of basic meteorological measurements, relative ease of deployment and maintenance, and fitness for purpose, particularly their ability to enhance observational coverage in settings where conventional stations are not feasible. At the same time, this category encompasses a wide spectrum of technologies with substantial variation in sensor quality, calibration standards, durability, and data reliability. Devices at the lower end of the price range may prioritize affordability and operational simplicity but offer limited precision or robustness, whereas higher-end systems within the same cost band may aim to deliver near scientific-grade measurements while maintaining moderate cost structures. Careful assessment of technical specifications, validation evidence, and operational requirements is therefore essential when selecting an appropriate technology within this heterogeneous market segment.

Local validation is a critical step before committing to large-scale operational use. Performance characteristics can vary across agroecological zones, elevation gradients, humidity regimes, and

connectivity environments, and what works well in one setting may not transfer directly to another. Co-location with reference-grade meteorological stations, side-by-side comparison with manual rain gauges, and systematic assessment of data completeness and transmission reliability are recommended approaches for verifying measurement accuracy under local conditions. Skipping this step carries the risk that undetected measurement bias or systematic error propagates into analytical outputs and undermines conclusions that depend on them.

The Arable Mark 2 is one example of this emerging category. At the time of the Uganda CLASS, the unit cost of a basic device was USD 899, compared to an estimated USD 23,000 for a professional automatic weather station of the type recommended by the DMS — roughly a 25-fold difference. Arable was selected for the study on the basis of its combination of demonstrated scientific-grade accuracy and moderate cost.

The Arable Mark 2 is a compact, integrated in situ weather and crop-monitoring device designed to collect high-frequency meteorological and environmental data through a single, solar-powered IoT platform. The system combines acoustic rainfall measurement, multispectral radiation sensing, atmospheric temperature and humidity monitoring, and cloud-based data processing within a unified hardware-software ecosystem. Data are logged at fine temporal resolution and transmitted via cellular connectivity to a centralized cloud infrastructure, where automated aggregation, calibration, and visualization tools are applied.

The device measures more than 40 climate and plant variables and uses built-in models to translate raw data into practical indicators for crop management. A comprehensive description of the device's technical specifications, sensor architecture, and measurement capabilities is provided in Annex 1.

Key advantages of the Arable device include ease of deployment, minimal maintenance requirements, and proven performance in agroecological environments comparable to those found in Uganda.[4] The Arable system enables real-time data verification through a synchronized mobile application, while hourly and daily datasets can be accessed and exported via the Arable web portal or programmatically through an Application Programming Interface (API) (see subsection 4.2 for additional details). These features facilitate integration with other data sources, including survey datasets, external meteorological records, and broader analytical workflows.

This section uses the Arable Mark 2 as an illustrative example to examine key technical and operational considerations in the deployment of in situ weather sensors within survey and operational contexts. The discussion focuses on planning and installation procedures, data transmission and retrieval mechanisms, and post-deployment monitoring arrangements, drawing on implementation experience from the Uganda CLASS. While many of the principles and procedural steps described are broadly applicable to other low-cost sensor platforms, certain elements — particularly those related to data retrieval processes and system architecture — are specific to the Arable device used in this study.

[4] Arable devices have been deployed in multiple countries across Sub-Saharan Africa, including Kenya, Mozambique, Rwanda, South Africa, Ghana, and Sierra Leone.

4.1 Planning and Implementing Weather Sensors Deployment

Careful planning of weather sensor deployment is essential to ensure data quality, operational sustainability, and alignment with survey or project objectives. In situ sensors can be deployed under different configurations depending on their intended use and the capabilities of the selected technologies and devices (e.g., some platforms, such as Arable, measure weather parameters while also providing crop intelligence, forecasting, and advisory services to farmers). In some contexts, sensors can be installed directly in farmers' fields to support crop monitoring and agronomic analysis, for example in the case of agricultural development projects or interventions. In others, sensors can be deployed at strategically selected community-level locations to strengthen local weather observation networks and support survey-based analysis.

This section outlines key considerations for planning the deployment of weather sensors across these configurations, covering procurement and initial preparations, followed by site identification, installation, and deployment processes. While the discussion draws on the Uganda CLASS implementation experience, the principles and technical considerations are broadly applicable across survey and operational contexts.

Procurement and Preparation

Early procurement and preparation activities constitute the first step in the process. These arrangements should be aligned with survey or project timelines, institutional capacity, and the intended deployment model, and should clearly define roles and responsibilities across participating actors.

Procurement typically involves engagement with the technology provider to define the scope of services, including hardware provision, data access modalities, technical support, and maintenance arrangements. Attention should be paid to providers' business models, as this is a relatively new and rapidly evolving space in which diverse solutions are offered. These models should be assessed considering project objectives and operational requirements. An illustrative overview of the Arable business model, based on the Uganda CLASS experience, and the related operational considerations is provided in Box 1.

Box 1. Arable Business Model: Overview and Operational Considerations

When choosing low-cost sensors for weather data collection, it is important to look not only at how well the technology works, but also at the business model of the provider. Business models affect overall costs, access to data, flexibility in operations, and the long-term sustainability of monitoring activities. Contract terms, ownership of equipment, and the way services are bundled can strongly influence project planning, budgeting, and risk management over the lifetime of a monitoring initiative.

Originally, the Arable business model offered two options: direct purchase of hardware and subscription-based services. More recently, the company has moved to a fully subscription-based model, with no option to buy the hardware outright. Access to the system is now provided through a minimum one-year contract, with lower annual fees for longer-term commitments. The subscription typically includes the following components:

- Hardware lease: Use of the selected sensor configuration for the duration of the contract.
- Data package: Ongoing access to collected weather and environmental data, including data storage and visualization tools.
- Technical support: Customer support, software and firmware updates, and system maintenance.
- API access: Automated access to data for use in other platforms or analysis systems.
- Limited warranty: Coverage for hardware faults under normal use, with optional damage insurance available at extra cost.

For research and development projects, this subscription model offers several benefits. It allows sensors to be deployed quickly, reduces the need for upfront investment, and limits the need for in-house technical expertise by bundling hardware, data access, and support into a single service. This makes the model well suited to short- to medium-term projects or pilot studies where flexibility and ease of management are important.

For National Meteorological Services and other operational agencies, the model requires more careful assessment. While integrated services and vendor-managed maintenance can simplify operations, long-term reliance on subscriptions may result in higher total costs over time and no ownership of physical equipment. For long-term, nationwide, or operational monitoring networks, it is important to consider contract length, long-term pricing, data ownership and access rights, compatibility with existing systems, and options for existing or changing providers. In many cases, subscription-based solutions may be best used to complement existing observation networks or to fill specific data or research gaps, rather than replacing core monitoring infrastructure.

It is also important to note that systems such as Arable are widely used by farmers and agri-businesses in developed countries, where the main goal is to support day-to-day farm management and decision-making. In these settings, subscription-based models work well because users value convenience, integrated services, and ongoing support more than owning the hardware. In developing-country contexts, however, similar technologies are also considered for public purposes such as expanding observation networks, supporting early warning systems, or improving climate services. In these cases, long-term affordability, local ownership, and institutional control of data and infrastructure become more important. This difference highlights the need to carefully assess whether business models designed for commercial agriculture are suitable for publicly funded or development-focused monitoring programs.

At the same time, implementation partners with the required technical capacity, such as national meteorological agencies, implementing agencies, or local technical teams, should be identified to support installation, monitoring, and field-level coordination. Where necessary, these partners should receive training to ensure they fully understand the technology and operational requirements and can support the process sustainably over time. Such training also strengthens local capacity through exposure to and hands-on experience with new technologies and innovations.

Clear delineation of responsibilities is particularly important at this stage. Responsibilities may be shared across the following actors:

1. Survey or project implementers, responsible for alignment with survey or project design, sampling considerations, data integration, and analytical use;

2. Technical implementing partners, responsible for field coordination, installation, and routine monitoring;
3. Technology providers, responsible for the timely supply of sensor hardware (including replacement units where necessary), data calibration and underlying modeling (e.g., for error correction or forecasting, where applicable), provision of sensor data records, and technical support.

Preparation activities at this stage may also include:

- Procurement of additional installation materials (e.g., mounting poles, compasses, tape measures, shovels);
- Development of installation guidelines and standardized checklists;
- Training of technical staff involved in installation and monitoring;
- Configuration of digital tools (e.g., CAPI forms, mobile applications) to support installation documentation and deployment tracking.

Teams should also factor device durability into procurement planning. Based on the Uganda CLASS experience, a share of Arable Mark 2 devices will require replacement within a two-year deployment window due to hardware failures — the frequency and spatial distribution of which are documented in Section 3.2. While the Mark 2 is designed for multi-year operation, failure rates observed in the field suggest that planning for replacements from the outset, rather than reactively, is prudent. Newer generations of the technology, such as the Arable Mark 3, are expected to address several of the hardware limitations observed in the Mark 2 and may reduce failure rates in future deployments. Nonetheless, regardless of the technology used, building in a reserve of replacement units sized according to anticipated failure rates and expected study duration remains good practice.

Deployment Configurations and Site Selection Principles

Site identification is a critical determinant of data accuracy, system reliability, and long-term sustainability. From a survey perspective, appropriate site selection ensures the analytical relevance of weather data. From an operational perspective, it underpins feasibility, physical security, and continuity of data transmission. The criteria and processes for site identification vary depending on the intended deployment model and the capabilities of the selected technologies and devices:

A. In field-based deployment, sensors are installed on individual farms or plots. Site selection prioritizes proximity to crops and soil conditions of interest and may support additional use cases such as crop monitoring or farmer decision support.
B. In community-level or network-oriented deployment, sensors are installed at centrally located sites (e.g., public facilities). Site selection prioritizes spatial representativeness, long-term accessibility, physical security, and integration into broader observation networks.

In the Uganda CLASS, Arable Mark 2 sensors were deployed under the community-level configuration. Emphasis was placed on identifying central, secure locations within communities to support the methodological and analytical objectives of the study rather than on-field crop monitoring. While some planning considerations discussed below are specific to this model, many — particularly technical considerations — are applicable across deployment configurations.

Effective community-level site identification should involve early engagement with district-level authorities, local leaders, and potential host institutions. Public facilities, such as government offices, health centers, or training institutions, are often preferred due to their relative security, accessibility, and institutional continuity. Depending on the context, private or community-owned sites (e.g., government farms or model farmers' premises) may also be suitable. [5]

Core criteria guiding site selection should include:

a) Adequate atmospheric exposure, free from obstructions that could bias measurements
b) Minimal ambient interference that could affect sensor performance (e.g., noise affecting sensors that rely on acoustic rainfall measurement)
c) Reliable network connectivity to support data transmission
d) Willingness of the host institution or landowner to accommodate the device
e) Physical security to minimize risks of tampering or theft (e.g., fencing or controlled access)
f) Availability of a designated on-site caretaker to safeguard the equipment and conduct routine monitoring following installation.

To ensure consistency and transparency, these criteria are best assessed using standardized tools. In the Uganda CLASS, a dedicated installation questionnaire implemented in CAPI guided the DMS technical staff through site assessment, documented compliance with selection criteria, and recorded consent and caretaker arrangements. Similar instruments can improve consistency, support real-time quality control, and generate auditable metadata. Annex 2 provides an example of the installation questionnaire used in the Uganda CLASS, along with the associated materials and equipment checklist.

Installation Procedures

Installation procedures should follow standardized technical guidelines to ensure consistency across sites and overtime. In the Uganda CLASS, installation followed guidelines jointly developed by implementing partners and Arable and included the following steps:

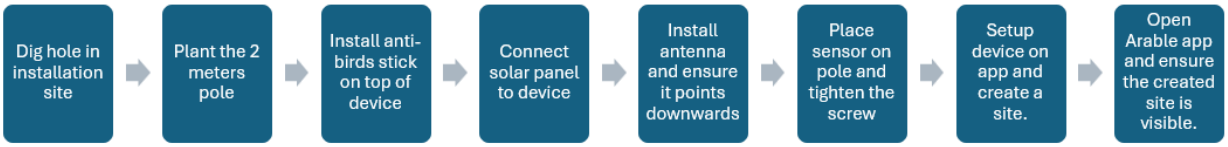
1. Engagement with local leaders and host institutions to secure community support;
2. Formalization of agreements with landowners and caretakers;
3. Completion of a site scoping checklist and deployment of sensors guided by a CAPI-based installation questionnaire;
4. Post-installation testing to verify power supply, connectivity, and data transmission using manufacturer-specific applications.

Community engagement was an integral part of the installation process to facilitate site access, ensure local awareness, and support ongoing oversight of deployed devices. Box 2 provides further detail on the community engagement approach adopted in the Uganda CLASS and the role of local caretakers in supporting device sustainability over time.

[5] In the Uganda CLASS, the majority of sensors (97.34 percent) were installed at model farmers' premises, with the remainder installed at sub-county offices and government farms.

Adherence to standardized procedures during the installation phase helps ensure comparability across sites and reduces the likelihood of measurement bias arising from inconsistent installation practices. Figure 7 illustrates the sequence of steps followed for the installation and deployment of the Arable Mark 2 in the Uganda CLASS, while detailed technical guidance specific to Arable Mark 2 installation and deployment is provided in Annex 3.

Figure 7. Installation steps followed in the Uganda CLASS for deployment of Arable Mark 2.



For installations at co-location sites (i.e., where sensors are deployed alongside third-party weather stations), additional technical rules should be followed. These requirements depend on the specific technology and manufacturer guidance. In the Uganda CLASS, the following principles were applied, based on recommendations from Arable:

- The sensor should be installed within approximately 2.5-3 meters of the third-party weather stations weather station;
- Deployment height should be consistent across stations; specifically, the sensor should be installed at the same height as the third-party station's rain gauge;
- The third-party station's rain gauge should be properly calibrated;
- Deployment sites should avoid environments with persistent background noise (e.g., generators, railway tracks, or busy roads), as this may affect acoustic rainfall measurement;
- Photographic documentation of the installation should be collected for verification and record-keeping purposes.

Post-Installation Monitoring and Follow-Up

Following deployment, an initial monitoring period is recommended to identify early issues related to connectivity, power supply, or environmental interference. Early detection of such issues is critical to minimizing data gaps.

Over time, monitoring efforts may focus on safeguarding the most vulnerable components (e.g., solar panels or antennas), informed by observed risks such as interference by animals or children. Monitoring may combine remote data checks with periodic field inspections and coordination with designated on-site caretakers.

A structured monitoring system strengthens system reliability, supports rapid troubleshooting, and enhances the long-term sustainability of deployment. Box 2 provides details on the monitoring arrangements implemented in the Uganda CLASS, including the integration of caretaker engagement, remote monitoring, and periodic field inspections.

Box 2. Community Engagement, Caretaker Roles, and Monitoring Arrangements in the Uganda CLASS

Community engagement was a critical enabling factor for the successful and sustainable deployment of weather sensors in the Uganda CLASS. Community sensitization, conducted through meetings with local leaders, public forums, and radio broadcasts, helped clarify project objectives, address concerns, and reinforce the non-intrusive nature of the project. This was particularly important in contexts where communities were unfamiliar with the technology or where concerns about monitoring and data use could arise.

Beyond sensitization, the structured involvement of local actors through the designation of on-site caretakers played a central role in maintaining devices functionality over extended periods. Local caretakers were responsible for routine visual inspections, safeguarding equipment, and reporting technical or security issues to implementing partners. Their role was observational rather than technical, focusing on basic monitoring tasks, issue identification, and communication protocols rather than equipment repair.

Engaging local caretakers also strengthened local ownership and contributed to capacity building by providing hands-on exposure to new technologies. Clear agreements regarding roles, responsibilities, reporting procedures, and compensation arrangements were essential to sustain engagement and accountability.

Caretaker engagement was complemented by a structured monitoring system led by the DMS technical team. Field inspection visits were conducted approximately every three months. During these visits, DMS staff completed standardized monitoring forms (Google-based) to document site conditions, operational challenges, and required follow-up actions. Monetary compensation covering the preceding three-month period was provided to caretakers during these visits. Annex 4 provides a summary of monitoring findings from the initial inspection rounds. Between field inspections, remote monitoring was conducted through regular phone contact with caretakers to identify and address emerging issues.

This combined approach — centered on community engagement, clearly defined caretaker roles, periodic field inspections, and continuous remote monitoring — and made feasible by the minimal maintenance requirements of the Arable Mark 2 technology, contributed to the absence of reported damage or security incidents throughout the implementation period.

4.2 Data Transmission and Retrieval

This subsection describes data transmission, access, and processing procedures specific to the Arable Mark 2 platform.

How Data Are Collected and Transmitted

The Arable Mark 2 replaces manual weather recording with an automated, cloud-based system. Once installed, the device operates independently and follows a simple data flow:

1. **Data recording:** The device measures weather and environmental variables (e.g., rainfall, solar radiation, air temperature, and humidity) every five minutes.
2. **Data transmission:** The device sends recorded data to the cloud using cellular connectivity (e.g., LTE-M, NB-IoT, or 2G). By default, data are synchronized approximately once per hour.

3. **Data processing:** After transmission, the Arable cloud system organizes the five-minute data into hourly and daily summaries. Automated corrections and quality checks are applied before the data becomes available to users.

This structure enables near real-time access to weather information without requiring manual downloads or on-site data retrieval.

Accessing Data via the App and Web Portal

Arable provides synchronized mobile and web interfaces that allow users to view and monitor data without additional processing.

Key features include:

- Fleet management: For multiple devices, the web dashboard provides a map view and device list, showing battery status, signal strength, and last synchronization time.
- Real-time monitoring and alerts: Users can receive notifications for rainfall, frost, heat events, or device inactivity. Alert thresholds can be customized.
- Historical analysis: Users can generate charts and compare weather trends across locations and seasons.

Automated Data Retrieval via Application Programming Interface (API)

For surveys and research projects, data can be downloaded automatically using the Arable Developer API. This allows integration with statistical software and analytical workflows (e.g., in Python or R). [6]

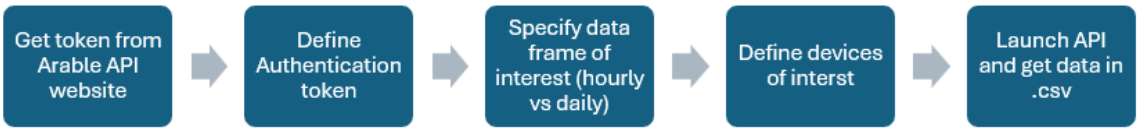
Data can be retrieved at three main temporal levels, with limits applying to the maximum time span that can be requested per query:

- 5-minute data: High-frequency raw observations (queries limited to a maximum of 7 days per request)
- Hourly summaries: Aggregated agrometeorological variables (queries limited to 100 days per request)
- Daily summaries: Longer-term indicators and crop-related indices (queries limited to 2 years per request).

Retrieved datasets typically include air temperature, humidity, rainfall, radiation, and vegetation indices such as NDVI. Data can be exported in standard formats (e.g., CSV or JSON) and require secure authentication credentials provided by Arable. Figure 8 summarizes the main steps required to retrieve data from the Arable API.

[6] Customizable code examples in both Python and R can be provided as supplementary files accompanying this technical note upon request.

Figure 8. Steps for data retrieval via the Arable API.



Data Processing and Quality Considerations

To ensure data quality and enable accurate comparability with other meteorological records (e.g., from other weather stations, or remote sensing-based data products), some key processing steps are recommended:

1. Time alignment: All Arable data are stored in GMT (UTC). For local analysis, timestamps should be converted to local time or aligned with the time convention of the dataset used for comparison. This is particularly important when comparing Arable data with manual rain gauge records, which often follow predefined observation windows. For example, for the manual rain gauge operated by the Uganda DMS, rainfall totals are calculated over a 24-hour period running from 06:00 GMT (09:00 Uganda Time) on day 1 to 08:59 GMT on day 2. This means that, for example, rainfall for January 1 should be computed as the sum of rain recorded between 06:00 GMT (09:00 Uganda Time) on January 1 and 08:59 GMT on January 2.
2. Aggregation level: Although the device records data at five-minute intervals, most analytical applications rely on hourly or daily summaries. Hourly data are useful for identifying short-duration events (e.g., peak rainfall intensity), while daily data are generally adequate for climate monitoring and agricultural productivity analysis.
3. Managing missing data: Data gaps may occur due to network interruptions, temporary power loss, or sensor malfunctions, as discussed in subsection 3.2. Missing values should not automatically be treated as zero, particularly for rainfall. Short gaps (e.g., less than three hours) may be addressed through interpolation, whereas longer gaps — especially those spanning multiple days — may require more careful imputation strategies or exclusion from comparative analyses. Rainfall data requires particular attention: transmission delays may result in accumulated totals being reported after connectivity is restored. In such cases, values may need to be redistributed across the missing period based on supporting information or excluded if the timing of the rainfall cannot be reliably determined.

5. Value Proposition of Low-Cost In Situ Weather Sensors

The Uganda CLASS represents a first proof of concept for the use of low-cost in situ sensors in agricultural data collection in a low-income country setting. While findings from a single pilot study in one country and one season should be interpreted with appropriate caution, the results offer an early but concrete basis for considering how sensors of this type might be integrated into agricultural data systems more broadly. This section sets out that case across three dimensions: what these

sensors offer analytically, how they relate to existing data infrastructure, and what they cost relative to the benefits they provide.

What In Situ Sensors Offer

Ground-truth, field-level rainfall measurement addresses a gap that neither professional station networks nor satellite products can fill on their own. National station networks, where they exist, are typically sparse: in Uganda, automatic weather stations were present in only 47 percent of districts as of 2023, leaving large portions of the agricultural landscape unmonitored at the ground level. Satellite-based gridded products provide broad spatial coverage but operate at varying spatial resolutions that necessarily average away localized rainfall events that are most relevant to individual farming plots.

The Uganda CLASS results show that the gap between these two systems is not merely technical, but it has direct implications for the quality of agricultural analysis and the decisions that may depend on it. Specifically, the evidence points to three areas where low-cost in situ sensors can offer the clearest payoff:

- Extreme event detection. Sensors substantially outperform satellite products in capturing heavy and violent rainfall events; the episodes most likely to cause crop damage, waterlogging, or drought stress depending on their timing relative to the growing season. For early warning systems, insurance trigger design, and shock diagnostics, this difference is consequential: an undetected extreme event is an unmeasured risk.
- Validation and bias correction of satellite products. Satellite gridded products are the *de facto* standard in much of sub-Saharan Africa, precisely because ground alternatives are scarce. However, those products carry systematic biases — overrepresenting light rainfall, underrepresenting heavy events, and smoothing intraseasonal variability — that are difficult to diagnose without reliable local benchmarks. A network of in situ sensors, even a modest one, can provide the reference data needed to quantify and, in some cases, correct those biases for specific locations and seasons. This use case is particularly valuable where long-term sensor deployment is feasible, as it can progressively improve the quality of existing gridded products for the study region.
- Credibility of agricultural inference. The econometric results from the Uganda CLASS study illustrate a specific and underappreciated risk: that yield–rainfall relationships estimated using satellite data may reflect measurement noise rather than genuine agronomic signals. This matters for the credibility of agricultural statistics, for yield modelling used in official monitoring systems, and for the design of climate-smart interventions.

Complementarity, Not Replacement

A key implication of this evidence is that low-cost in situ sensors are most valuable as a complement to existing data infrastructure, not as a substitute for it. Professional weather stations remain the authoritative benchmark: they provide the longest historical records, the highest measurement precision, and the institutional foundation for national climate services. Satellite products remain indispensable for their geographic reach; no ground network, however dense, can match the spatial coverage that satellite observations provide at scale. What in situ sensors add is a middle layer: field-

level accuracy, intraseasonal resolution, and local validation capacity that neither professional stations nor satellites can supply in data-sparse settings.

The Uganda CLASS experience points toward a hybrid data architecture in which these three sources can play complementary roles: professional stations anchor the measurement system and provide long-run climatological records; satellite products extend coverage across geography and time; and low-cost in situ sensors provide localized ground truth that can be used to validate and, where appropriate, correct satellite-based estimates. This layered approach does not require replacing any existing infrastructure but rather it builds on it. National meteorological services, in particular, stand to gain from networks of lower-cost sensors deployed in collaboration with survey programs, as co-location data can strengthen the calibration of both local and gridded products over time.

Cost Considerations

Understanding the cost structure of sensor deployment is essential for assessing whether this approach is operationally feasible at scale. Table 2 below presents an indicative two-year budget for a 75-station network based on the Uganda CLASS experience, expressed in 2023 USD.

Table 2. Indicative two-year costs for a 75-station in situ sensor network (2023 USD)

Cost item	No. of units	Unit cost (USD)	Total (USD)
Technology procurement (one-off)			
Device (Arable Mark 2, standard configuration, incl. data services)	75	899	67,425
Protection insurance	75	100	7,500
Shipping costs	75	45	3,360
Installation (one-off)			
Pole	75	15	1,125
Concrete	75	2	150
Workforce for installation	5	300	1,500
Monitoring (two-year)			
Caretakers*	75	648	48,600
Inspection visits (staff time and logistics)**	75	437	32,775
Total			162,435
Cost of one day of data from one device			**~USD 3**

* Monthly stipend of USD 27 × 24 months = USD 648 per device. ** Four inspection visits per year over two years (8 total).

Note 1. Unit costs reflect the Arable Mark 2 procurement arrangement in place at the time of the Uganda CLASS. Prices may vary depending on the procurement model selected and evolving vendor offerings.

Note 2. Replacement devices are not included as a separate budget line. In the Uganda CLASS, replacement units were supplied by Arable at no additional cost under the terms of the procurement contract. Teams are strongly advised to negotiate a similar clause with their provider before deployment begins, specifying the number of replacement units the provider is obligated to supply given expected failure rates and project duration. Where such a clause cannot be secured, a contingency budget for replacement devices should be added to the table.

Note 3. Data storage, cloud processing infrastructure, and API access are not included as separate line items, as these services are typically bundled into the device cost depending on the procurement arrangement selected. Teams should verify what is and is not included in their chosen arrangement and budget for any unbundled data infrastructure costs separately.

Several features of this cost structure are worth noting. Upfront costs — covering the device, insurance, shipping, installation materials, and labor — and recurrent monitoring costs — caretaker remuneration and inspection visits — each account for roughly half of total two-year expenditure, with device procurement as the single largest line item. Within the monitoring component, caretaker remuneration represents approximately 30 percent of total expenditure over two years, suggesting that community engagement arrangements are not a peripheral consideration but a substantive cost driver that warrants careful budgeting alongside hardware procurement. More broadly, the Uganda CLASS experience suggests that savings or overruns over the life of a deployment are likely to hinge on two factors: the procurement price secured for devices, and how effectively caretakers can resolve minor issues locally and limit the need for field missions.

At a daily cost of approximately USD 3 per device, the overall cost profile appears competitive for dense, field-level observation in data-scarce settings, and compares favorably to the capital cost of professional automatic weather stations, estimated at roughly USD 23,000 per unit at the time of the study, approximately 25 times more expensive at the point of purchase, before accounting for ongoing maintenance. The cost structure also appears to leave room for programmatic additions — connectivity and data plans, spare parts kits, or periodic quality-control co-locations — without fundamentally altering the economic picture.

These figures do not constitute a cost-effectiveness analysis, which would require modelling the downstream benefits of improved measurement quality, a worthwhile exercise as evidence from this and similar pilots accumulate. What they suggest is that low-cost sensor networks may be financially accessible within the budget envelopes of large-scale agricultural surveys in low-income countries, particularly when deployment is integrated into existing fieldwork structures and community engagement processes rather than managed as a standalone infrastructure program. Replication across different contexts will be important for assessing how far these cost patterns generalize.

6. Lessons Learned and the Path Forward

The Uganda CLASS represents an early proof of concept, and its value lies not only in what it found but in what it opens up. The experience accumulated over two years of sensor deployment points to a set of practical considerations for teams looking to build on this work, whether by replicating the approach in other contexts, scaling it within Uganda, or integrating low-cost sensor data more systematically into national agricultural data systems.

Design validation in from the start. Co-locating sensors with professional meteorological stations was the methodological cornerstone of the Uganda CLASS performance assessment. Without those reference measurements, it would not have been possible to establish how well the low-cost sensors performed, or to quantify the limitations of satellite products in the study area. Any future deployment aiming to produce credible results should treat this as a design requirement rather than an optional add-on. Where existing meteorological infrastructure can be leveraged, early engagement with national meteorological services as partners in study design is strongly advisable. In Uganda, the Department of Meteorological Services played a central role. Equivalent partnerships in other countries will require similarly early and substantive investment.

Invest in the operational setup before deployment. Much of what determined data quality in the Uganda CLASS was decided before the first sensor was switched on: site selection, connectivity assessment, community engagement, caretaker arrangements, and logistics planning. These are not administrative details, they are the conditions under which the technology either works or does not. Future implementations would benefit from a structured pre-deployment phase that systematically addresses each of these dimensions, including connectivity checks at each proposed site, formal agreements with host farmers and caretakers, and in-country spare capacity for devices and components. The time invested at this stage pays off in data completeness and operational continuity during the deployment itself.

Make sampling choices deliberately to maximize the value of the network. Sensor placement is an analytical decision as much as a logistical one, and it deserves the same attention as the design of the survey instrument itself. In the Uganda CLASS, sensor locations were determined primarily by the structure of the existing survey sample, which was appropriate for the study's objectives but left limited room for optimizing the spatial configuration of the network for weather measurement purposes. Future deployments have an opportunity to be more intentional, for example:

- Co-location sites should be chosen to cover the agroclimatic variation present in the study area;
- EA-level sensors should be placed as close as possible to the plots and households they are intended to serve, minimizing the distance over which rainfall readings need to be extrapolated;
- A subset of sensors could be positioned specifically to validate satellite products across a range of rainfall regimes.

In constrained settings, where resources limit the size of the network, investing in the quality of the spatial design is likely to yield greater analytical returns than simply adding devices. The sensor network is most valuable when its design is treated as an integral part of the study's statistical architecture rather than a separate operational layer.

Evaluate the business model carefully before scaling. Low-cost sensor platforms vary considerably in how they are commercially structured, and the procurement model that suits a time-limited pilot may not be appropriate for longer-term or national-scale applications. Subscription-based arrangements that bundle hardware, data access, and technical support can reduce upfront capital requirements and simplify deployment, but they raise questions about hardware ownership, cost sustainability, and vendor dependency that deserve careful consideration before committing at scale. Where the goal is to build lasting institutional capacity, outright hardware ownership may be preferable, and partnerships with national meteorological services or public research institutions could offer a more sustainable path than reliance on a single commercial provider.

Finally, the Uganda CLASS results provide an early but concrete foundation for advocating greater investment in field-level weather observation in low-income country settings. The performance gap between in situ sensors and satellite products, and the implications of that gap for agricultural inference, are findings with direct relevance to national statistics agencies, agricultural ministries, climate adaptation programs, and development partners. Communicating these results effectively, and situating them within the broader case for data system investment, is itself an important next step. A single pilot is unlikely to shift institutional practice on its own; building a cumulative evidence

base across multiple countries and seasons, and linking that evidence to specific operational decisions, is what will ultimately justify the approach at scale.

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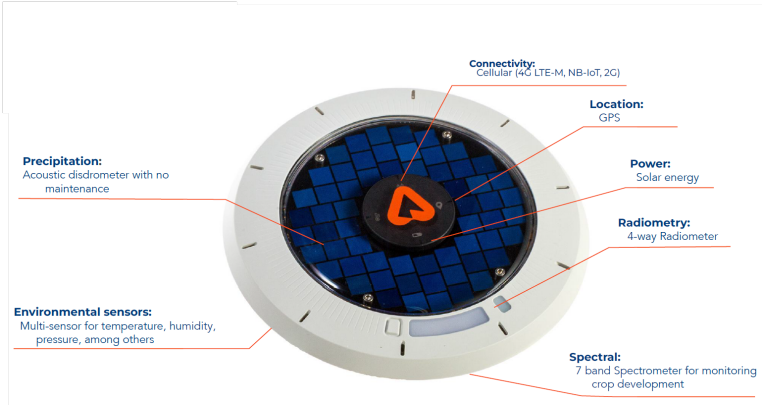
Annex1. Technical Specifications and Measurement Capabilities of the Arable Mark 2

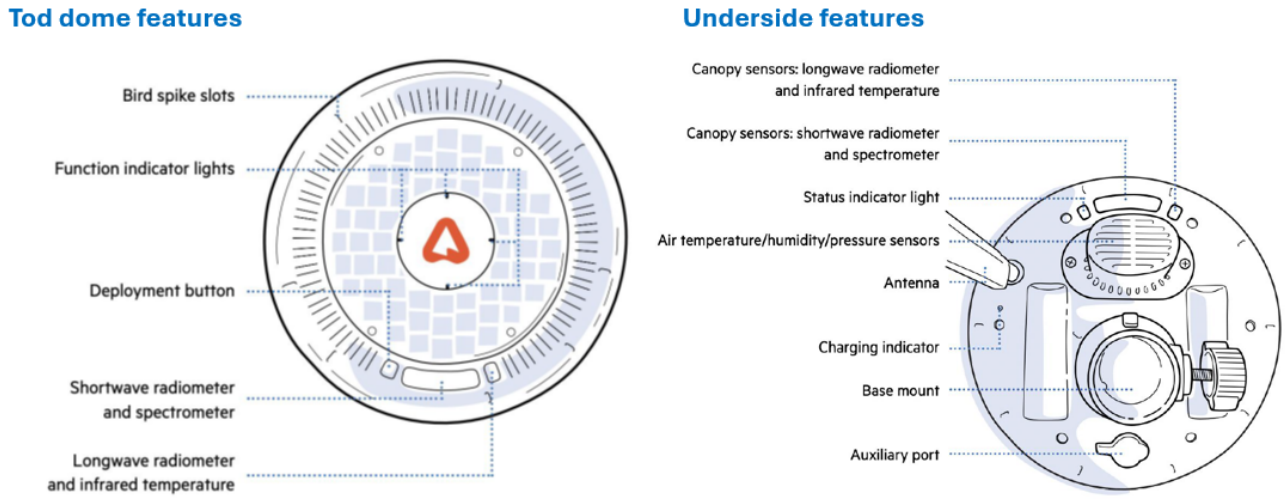
This annex provides a brief overview of the main hardware features, measurement capabilities, and connectivity components of the Arable Mark 2 system. The description draws on official Arable technical documentation (see https://support.arable.com/getting-started) as well as training materials developed and used for the Uganda CLASS.

Core Device

The Arable Mark 2 is an integrated, solar-powered, in-field sensing device designed to collect high-frequency weather, crop, and environmental data with minimal maintenance requirements. Multiple sensors are integrated into a single compact unit, enabling the measurement of over 40 climate- and plant-related variables.

Figure 2.1. Anatomy of the Arable Mark 2.





The device is designed for deployment in remote and data-sparse regions and operates continuously without external power or routine calibration. Its rugged enclosure (IP67-rated) and UV-resistant coating support long-term outdoor operation under harsh environmental conditions.

Additional technical specifications are available in the Arable Mark 2 technical documentation (see manufacturer documentation: Arable Mark 2 Product specifications).

Measurement Capabilities

The measurement capabilities of the Arable Mark 2 vary depending on the deployment configuration. The device can operate in a standard (core) configuration and, where required, in an augmented configuration with additional external sensors. When deployed over crops and configured accordingly in the platform, it also generates crop-specific indicators derived from environmental measurements.

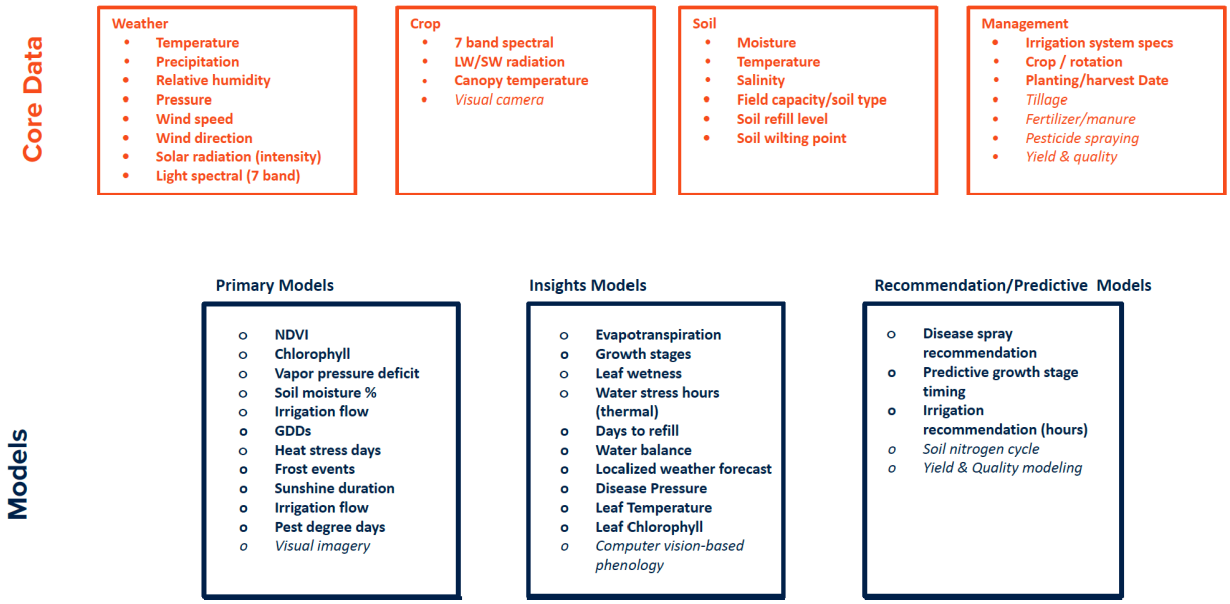
In its standard configuration, the Mark 2 records key atmospheric variables, including **air temperature**, **relative humidity**, **atmospheric pressure**, **solar radiation**, and **rainfall**. Rainfall is measured using an acoustic disdrometer that detects the impact energy of raindrops. This method avoids the use of tipping buckets and reduces mechanical maintenance requirements. The device also includes a four-way net radiometer and a seven-band spectrometer, which enable monitoring of radiation balance, canopy temperature, and vegetation-related spectral responses.

Where additional measurements are required, the system can be augmented with external sensors. Integration of an external anemometer enables measurement of **wind speed** and **wind direction**. Soil probes can be connected to capture **soil moisture**, **soil temperature**, and **other soil parameters** depending on the sensor type used. These additions extend the monitoring system beyond above-ground atmospheric conditions to include wind dynamics and below-ground soil processes.

When the device is installed over cultivated fields, the platform generates crop-specific derived agronomic indicators based on the measured weather and spectral data. These include **evapotranspiration (ETc)**, **growing degree days (GDD)**, vegetation indices such as **NDVI**, **plant water stress indicators**, **leaf wetness–based disease risk metrics**, and **radiation balance components** relevant to crop development. These indicators are computed through embedded models that combine environmental measurements with crop-specific parameters.

Additional technical details on core and model-based measurements, accuracy specifications, and precipitation methodology are available in the Arable Mark 2 technical documentation and white papers (see manufacturer documentation: Arable Mark 2 Measurements; Arable Mark 2 Core Measurements Accuracy Whitepaper; Arable Precipitation Whitepaper).

Figure 2.2. Arable Mark 2 core and model-based measurements.

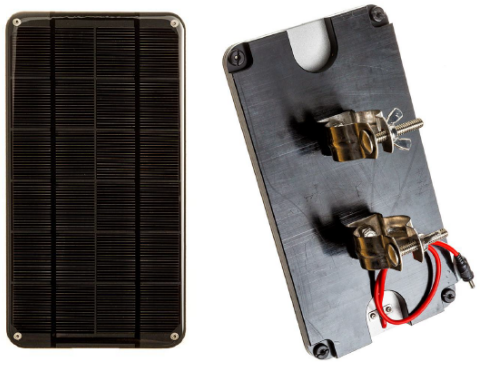


Power System and External Solar Panel

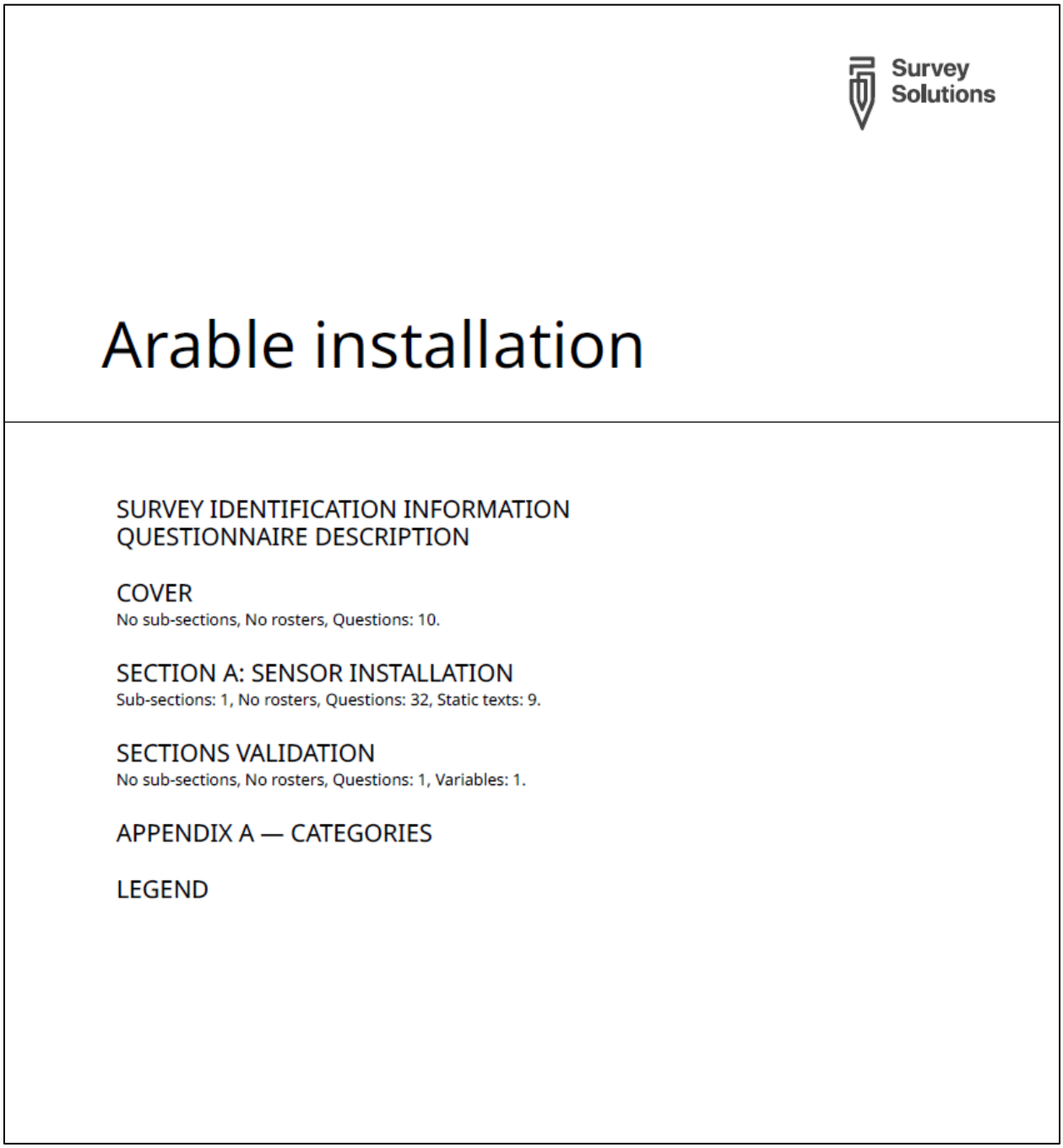
The Arable Mark 2 is equipped with an integrated solar panel and internal high-endurance lithium batteries, allowing continuous off-grid operation. In environments with limited solar exposure—such as regions with frequent cloud cover or partial shading—an external 5W solar panel can be added to supplement onboard power generation.

The external solar panel is mounted on the same pole as the device, typically 20–30 cm below the Mark 2, and oriented toward the equator to maximize solar gain. Correct installation improves power stability and reduces the likelihood of device downtime caused by low battery levels.

Figure 2.3. External solar panel for Arable Mark 2 and typical mounting configuration.



Annex 2. Example Arable Mark 2 Installation Questionnaire & Materials Checklist from the Uganda CLASS



Survey Solutions

Arable installation

SURVEY IDENTIFICATION INFORMATION
QUESTIONNAIRE DESCRIPTION

COVER
No sub-sections, No rosters, Questions: 10.

SECTION A: SENSOR INSTALLATION
Sub-sections: 1, No rosters, Questions: 32, Static texts: 9.

SECTIONS VALIDATION
No sub-sections, No rosters, Questions: 1, Variables: 1.

APPENDIX A — CATEGORIES

LEGEND

COVER

EA name	TEXT	ea_name
EA code	TEXT	ea_code
Region name	TEXT	reg_name
Region code	NUMERIC: INTEGER	reg_code
District name	TEXT	district_name
District code	NUMERIC: INTEGER	district_code
Enumerator name	TEXT	foname
Station for colocation	TEXT	station_colocation
Assigned Arable sensor barcode	TEXT	sensor_barcode
Assigned Arable solar panel barcode	TEXT	solar_barcode

SECTION A: SENSOR INSTALLATION

sa_sensorinstallation

ENUMERATOR: RECORD START TIME FO R SECTION A

DATE: CURRENT TIME — start_time_sa

MM/DD/YYYY

Where are you installing this sensor?

E IsAnswered(start_time_sa)

SINGLE-SELECT — sensor_install_where

- 01 ○ Health center
- 02 ○ Model farmer
- 03 ○ Sub county office
- 04 ○ Colocation site
- 05 ○ Government farm
- -96 ○ Other specify

Specify other

E sensor_install_where==-96

TEXT — sensor_install_where_o

Confirm that you are at the colocation s ite %station_colocation%

E sensor_install_where==4

SINGLE-SELECT — colocation_confirm

- 01 ○ Yes
- 00 ○ No

Enter the name of the installation place

E IsAnswered(sensor_install_where)

V1 self.ConsistsOf("ABCDEFGHIJKLMNOPQRSTUVWXYZ") && self.Length>0 && self.Length<=30

M1 Check the name entered, ALL CAPS. Numbers and !-?#@ not allowed

TEXT — name_installation_place

Is this site on a private land?

E IsAnswered(name_installation_place)

SINGLE-SELECT — is_privateland

- 01 ○ Yes
- 00 ○ No

Land responsible/owner name and sur name

V1 self.ConsistsOf("ABCDEFGHIJKLMNOPQRSTUVWXYZ") && self.Length>=1

M1 WRITE NAME IN ALL CAPS

TEXT — landowner_name

Contact number of the landowner/responsible I ENTER THE 10 DIGIT PHONE NUMBER EG. 0701035632 E `IsAnswered(landowner_name)` V1 `self.ConsistsOf("1234567890") & self.Length>=10` M1 ENTER THE 9 DIGIT PHONE NUMBER	TEXT ..... `landowner_phone`
Has the site responsible consented to the form? E `IsAnswered(landowner_name)`	SINGLE-SELECT 01 ○ Yes 00 ○ No `consent`
Take a picture of the signed consent I Enumerator: Once the land owner has agreed to the consent, take a picture of the signed consent E `consent==1`	PICTURE `consent_picture`
Scan the Arable sensor barcode E `IsAnswered(name_installation_place)` V1 `self==sensor_barcode` M1 Ensure that you scan the correct sensor	BARCODE `arable_barcode`
Scan the solar barcode E `IsAnswered(arable_barcode)` V1 `self==solar_barcode` M1 Ensure you scanned the assigned solar panel barcode	BARCODE `arable_solar_barcode`
Deploy the device, ensure that all the lights are green i.e. that connectivity is fine. I To deploy, click on the start button for 5 seconds. Wait for the blue blinking lights to become green. Give around 30 minutes for the connectivity light to turn green. E `IsAnswered(arable_barcode)`	SINGLE-SELECT 01 ○ Yes 00 ○ No `ensure_deployment`
STATIC TEXT E `ensure_deployment==0` *Take a picture of the issue and post it on the WB-ARABLE-UNMA whatsapp chat. You will get assistance*	
Is the issue solved? E `ensure_deployment==0`	SINGLE-SELECT 01 ○ Yes 00 ○ No `issue_solved`

SECTION A: SENSOR INSTALLATION

DEVICE DEPLOYMENT PROCEDURE

E `ensure_deployment==1 || issue_solved==1`

STATIC TEXT

Enumerator, you can now start the installation of the weather sensor. If you have any doubts, you can refer to the video at this link: https://www.youtube.com/watch?v=MMhTR162W3s. In case you have connection issues, a copy of the video is also available in your tablet (check the Arable installation folder on your tablet's home screen).

Arable sensor gps

E `IsAnswered(name_installation_place)`

GPS `arable_gps`

N ----------

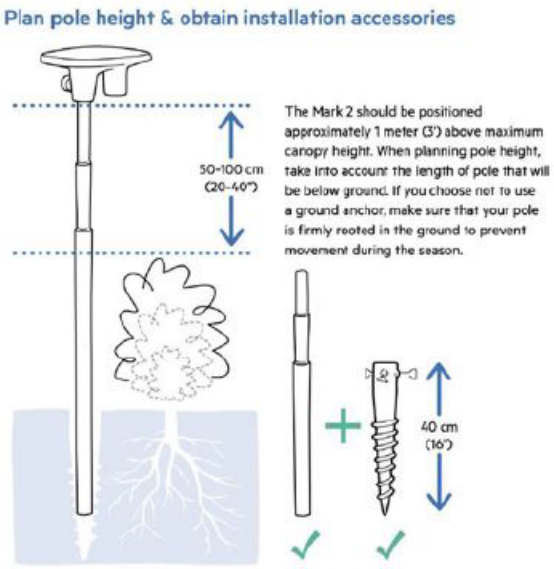
W ----------

A ----------

STATIC TEXT

E `IsAnswered(arable_barcode)`

Dig the hole in the soil, plant the pole



Have you digged the hole in the soil, pl anted the pole?

E `IsAnswered(arable_barcode) && IsAnswered(arable_gps)`

SINGLE-SELECT `checkpoint_pole`

01 ○ Yes

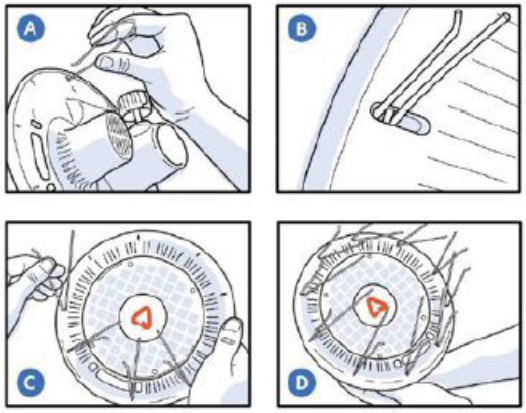
00 ○ No

STATIC TEXT

E `checkpoint_pole==1`

Install the anti birds sticks

deterrent spikes



Have you installed the anti birds sticks?

E `checkpoint_pole==1`

SINGLE-SELECT `checkpoint_birdsticks`

01 ○ Yes

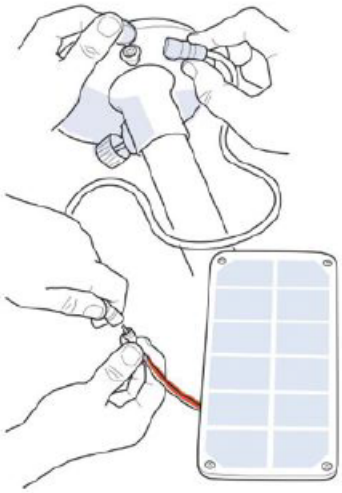
00 ○ No

STATIC TEXT

E `checkpoint_birdsticks==1`

Connect the solar panel to the device

B. If using only a Mark:



Have you connected the solar panel to t he device?

I Link the solar with the Mark2 cable and attach the panel 20 centimeters below the sensor itself

E `checkpoint_birdsticks==1`

SINGLE-SELECT `checkpoint_solar`

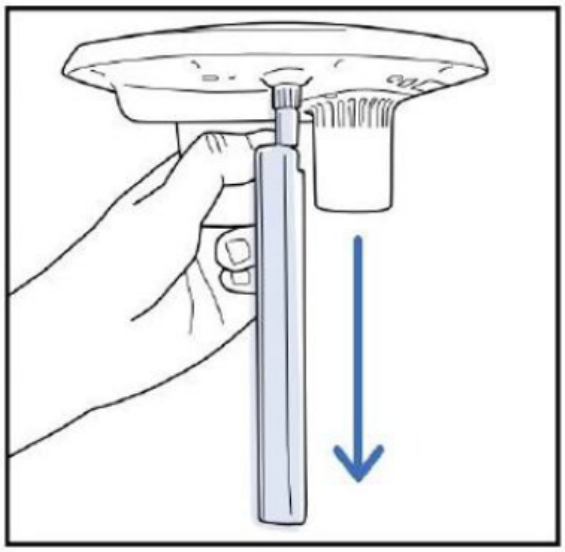
01 ○ Yes

00 ○ No

STATIC TEXT

E `checkpoint_solar==1`

Ensure the antenna is pointing downwards



Is the antenna pointing downwards?

E `checkpoint_solar==1`

SINGLE-SELECT `checkpoint_antennadown`

01 ○ Yes

00 ○ No

STATIC TEXT

E `checkpoint_antennadown==1`

Place the sensor on the pole and tighten the screw

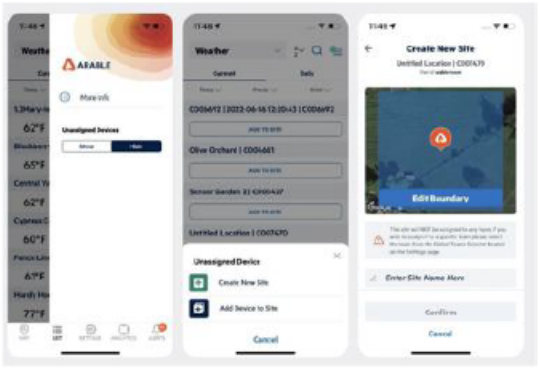


Have you placed the device on the pole and tightened the screw? E `checkpoint_antennadown==1`	SINGLE-SELECT 01 ○ Yes 00 ○ No	`checkpoint_placedonpole`

STATIC TEXT

E `checkpoint_placedonpole==1`

Setup the device on the app and create a new site for this sensor



Have you created a site for this device?

E checkpoint_placedonpole==1

SINGLE-SELECT checkpoint_createsite

01 ○ Yes

00 ○ No

Insert site name in the app. The site name should be: %name_installation_place%

I ENTER NAME IN ALL CAPS.

E checkpoint_createsite==1

V1 self.ConsistsOf("ABCDEFGHIJKLMNOPQRSTUVWXYZ") && self.Length>0 && self.Length<=30

M1 Check the name entered. Numbers and !-?#@ not allowed

W2 self==name_installation_place

M2 The site should be named as the installation place

TEXT site_name

Open the Arable app, is your device visible on the map?

E checkpoint_createsite==1

SINGLE-SELECT checkpoint_deviceonapp

01 ○ Yes

00 ○ No

Have you confirmed with Milton that the device is deployed?

E checkpoint_deviceonapp==1

SINGLE-SELECT checkpoint_milton

01 ○ Yes

00 ○ No

Arable sensor picture

I Place yourself at 1 meter from the sensor and take a picture

E checkpoint_milton==1

PICTURE arable_picture

STATIC TEXT

E checkpoint_milton==1

Congratulations: you have correctly deployed the sensor! Now please collect some information about the community observer

Respondent name and surname

E IsAnswered(arable_picture)

V1 self.ConsistsOf("ABCDEFGHIJKLMNOPQRSTUVWXYZ") && self.Length>=1

M1 WRITE NAME IN ALL CAPS

TEXT observerer_name

Contact number of the respondent

I ENTER THE 10 DIGIT PHONE NUMBER EG. 0701035632

E IsAnswered(observerer_name)

V1 self.ConsistsOf("1234567890") & self.Length>=10

M1 ENTER THE 9 DIGIT PHONE NUMBER

TEXT observerer_phone

Alternative contact number of the respondent I ENTER THE 10 DIGIT PHONE NUMBER EG. 0701035632 E IsAnswered(observerer_phone) V1 (self.ConsistsOf("1234567890") & self.Length >=10) || self=="-98" M1 ENTER THE 10 DIGIT PHONE NUMBER OR -98 IF NO ADDITIONAL PHONE NUMBER AVAILABLE	TEXT observerer_phonealt .....
Gender of the respondent E IsAnswered(observerer_phonealt)	SINGLE-SELECT observer_gender 01 ○ Female 00 ○ Male
Age in year of the respondent I In years E IsAnswered(observer_gender) V1 self>=18 && self<=70 M1 Age allowed between 18 and 70 years	NUMERIC: INTEGER observer_age ----------
Highest level of education attained. E IsAnswered(observer_age)	SINGLE-SELECT observer_education 10 ○ Some schooling but not Completed P.1 11 ○ Completed P.1 12 ○ Completed P.2 13 ○ Completed P.3 14 ○ Completed P.4 15 ○ Completed P.5 16 ○ Completed P.6 17 ○ Completed P.7 21 ○ Completed J.1 22 ○ Completed J.2 23 ○ Completed J.3 31 ○ Completed S.1 32 ○ Completed S.2 35 ○ Completed S.3 36 ○ Completed S.4 33 ○ Completed S.5 And 5 other symbols [5]
ENUMERATOR: RECORD END TIME FOR SECTION A E IsAnswered(start_time_sa) V1 IsAnswered(observer_education) M1 ANSWER REQUIRED	DATE: CURRENT TIME end_time_sa MM/DD/YYYY .....

SECTIONS VALIDATION

validations

VARIABLE NumberUnansweredQuestions(sa_sensorinstallation)	DOUBLE	num_unans_sa
ENUMERATOR: CAPTURE THE END TIME OF THE INTERVIEW	DATE: CURRENT TIME MM/DD/YYYY	endtime

Materials and equipment checklist:

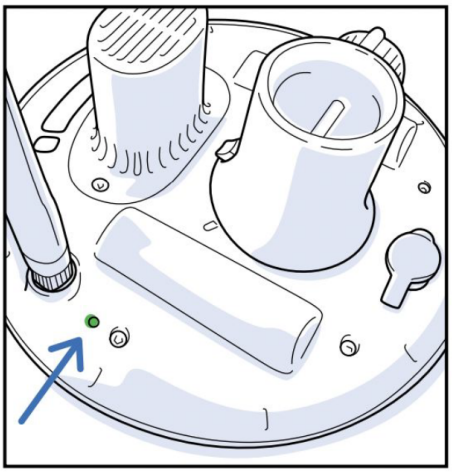
	Qty x Team Leader	Total Qty	Status
Arable Mark 2 box containing: - Mark 2 device - Solar panel - Charger - Bird spikes	17 (16 + 1 backup)	85	þ
Mounting pole	16	80	þ
Extension cables	1	5	þ
Installation material kit (cement, sand, etc.)	16	5	
Tablets (with Interviewer app + Arable app installed) + charger	1	5	þ
Compass	1	5	þ
Spirit level	1	5	þ
Tape measure	1	5	þ
Deployment manual	1	5 copies	þ
List of sample EAs + colocation sites	1	5 copies	þ
Arable training slides print out	1	5 copies	þ
External antennas (for later)	1	5	þ
Notebook + pen	1	5	þ

Annex 3. Arable Mark 2 Deployment and App-Based Configuration Procedures

This annex contains step-by-step guidance for installing and configuring the Arable Mark 2 in field, including physical deployment, connectivity setup, and mobile/web application configuration. The guidance is based on information from the Arable Support portal (https://support.arable.com/)[7] as well as on training materials specifically developed by Arable for this study to train the Uganda Department of Meteorology (DoM) team.

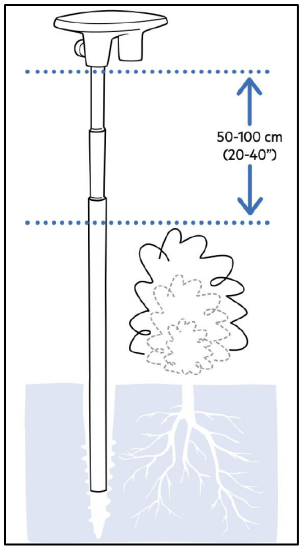
Physical Installation

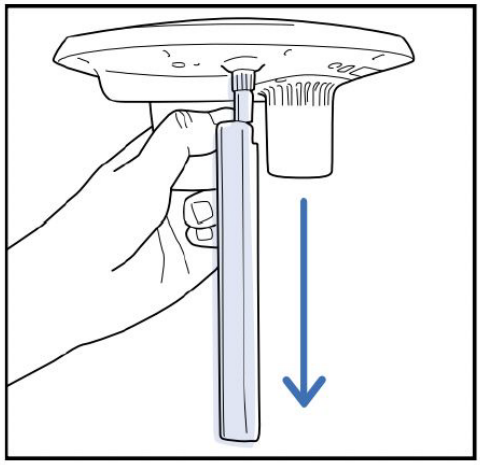
1) Before going to the field for deployment, the Mark 2 device should be fully charged using its AC power adapter. The charging indicator light, which is on the underside of the device (see Annex 1), shows orange when charging and turns green when fully charged, as illustrated below:



2) Deployment begins with proper mounting of the device on a stable pole anchored securely in the ground. Arable Mark 2 units are typically installed at a height of approximately 1.5-2 meters above ground level, or roughly 1 meter above the maximum crop canopy height where applicable (e.g., when crop monitoring is an objective). The device should be installed with the antenna pointing downward, as illustrated below:

[7] Mark 2 documentation on the Arable Support portal has since largely been replaced by Mark 3 materials, although deployment procedures remain broadly similar.

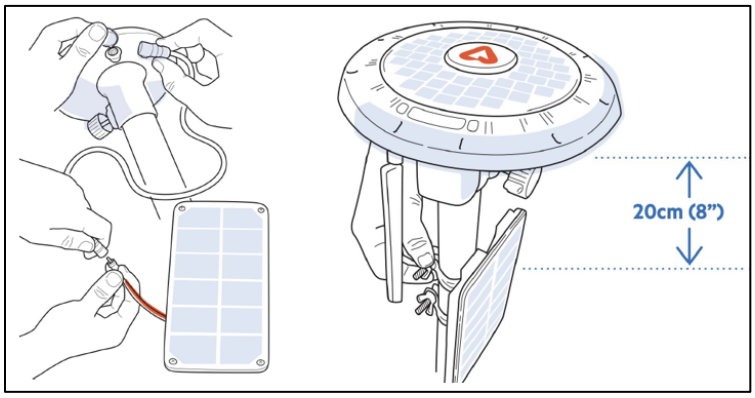




The canopy-facing sensors located on the underside of the device (see Annex 1) should be positioned above the crop canopy and oriented toward the equator. Surrounding obstructions such as trees, buildings, or fencing should be avoided to minimize interference with radiation and rainfall measurements.

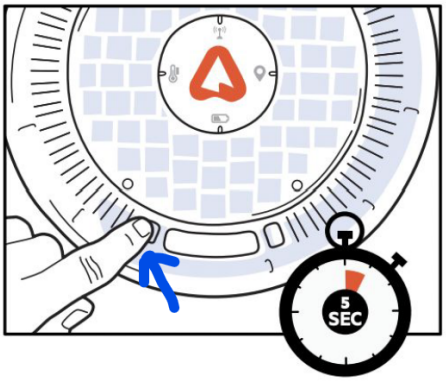
When the Mark 2 is co-located with a reference weather station for validation or calibration purposes, the device should be installed within approximately 2.5-3 meters of the reference station and at the same measurement height as the reference rain gauge. Height alignment and spacing should follow the applicable co-location protocol.

If an external solar panel is used, it is mounted on the same pole as the Mark 2, typically 20-30 cm below the device. The panel should be securely fastened to the pole and oriented toward the equator to maximize solar gain. Correct installation improves power stability and reduces the likelihood of device downtime caused by low battery levels. The solar cable is connected either directly to the device or through the Arable Bridge (a connectivity and power interface module that enables integration of external power sources and antennas) depending on the deployment configuration, as illustrated below:



Field Deployment and Connectivity Configuration

3) The Mark 2 is controlled by one button. The length of the button press determines the function. After physical mounting, the device is activated using the deployment button located on the top dome. A medium press (approximately 5 seconds) initiates the deployment sequence, as illustrated below:





SHORT PRESS < 2 seconds
Function: Check deployment status



MEDIUM PRESS 5 - 10 seconds
Function: Turn on/off (deploy/undeploy)



LONG PRESS 15+ seconds
Function: Reset device
*On long press, all four function indicator lights flash blue for 5 seconds and then turn OFF. Once this happens, the device will return to the deployment state it was in prior to reset.

> ***!! IMPORTANT**: Wait until reaching the planned installation location before attempting deployment. Device will not successfully deploy indoor.*

The indicator lights flash blue during boot-up and connectivity checks. A sequence of green lights indicates successful deployment:

a) Flashing blue lights = connecting



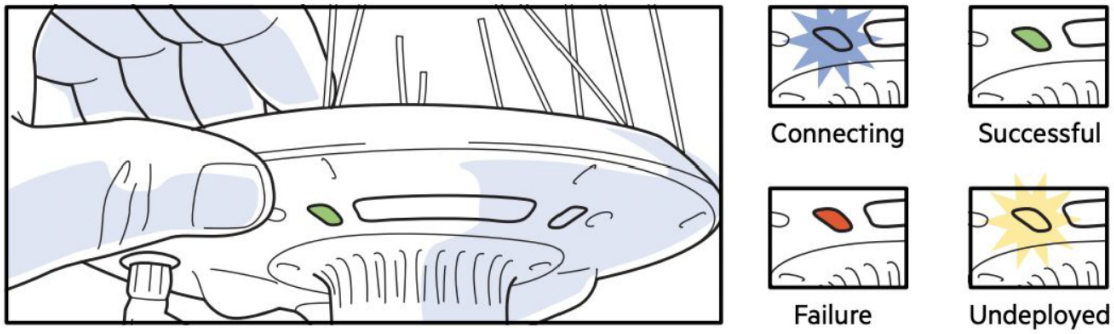
b) All green lights = successfully deployed:



> ***!! IMPORTANT**: There may be a delay of up to 20 seconds between indicator lights as the Mark 2 progresses through the deployment sequence. The full deployment process may take several minutes, depending on local connectivity conditions. Do not attempt to redeploy the device during this period, as time is required to establish a network connection.*
>
> *Deployment and undeployment use the same procedure: press and hold the deployment button for approximately 5 seconds. Do not press and hold the button more than once, as this will cause the device to undeploy.*

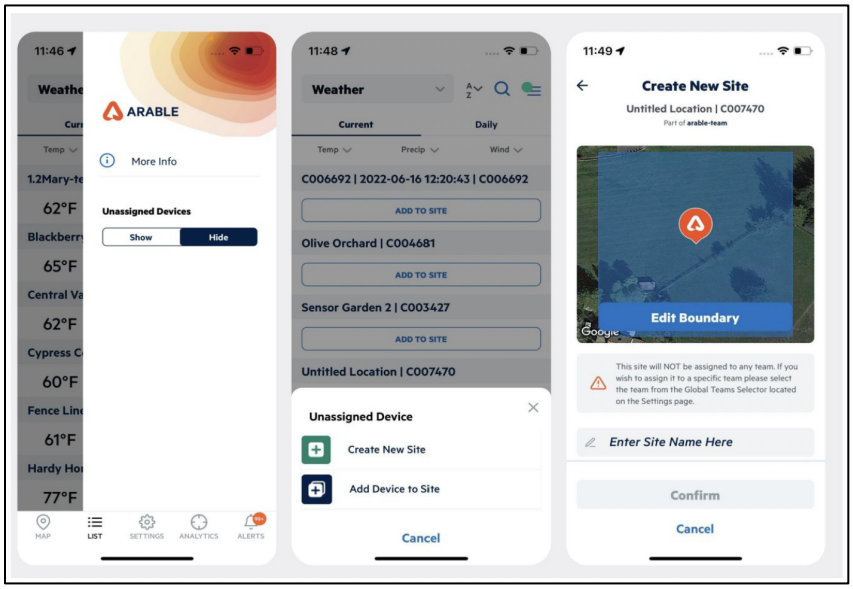
At sites with poor signal strength, directional external antennas may be installed to boost connectivity. These antennas are mounted on the deployment pole approximately 30-45 cm below the Mark 2 and oriented toward the nearest cellular tower or strongest signal source. The use of external antennas can substantially reduce data transmission delays and inactive sensor events in low-coverage areas.

4) Verify deployment by short-pressing the button (< 2 seconds) and check the status indicator light on the underside device:



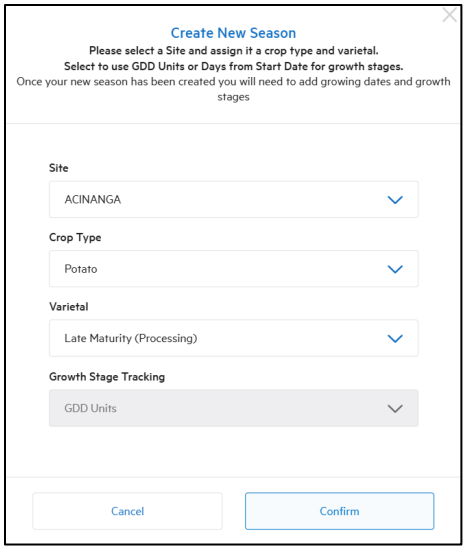
Device Assignation and Mobile App Configuration

5) Deployment of the Mark 2 is integrated with the Arable mobile application, and digital configuration occurs alongside physical installation. After the device has been successfully deployed, it must be assigned in the mobile app using its unique identifier. The installer can either create a new site or assign the device to an existing site located within a 10 square km radius, as illustrated below:



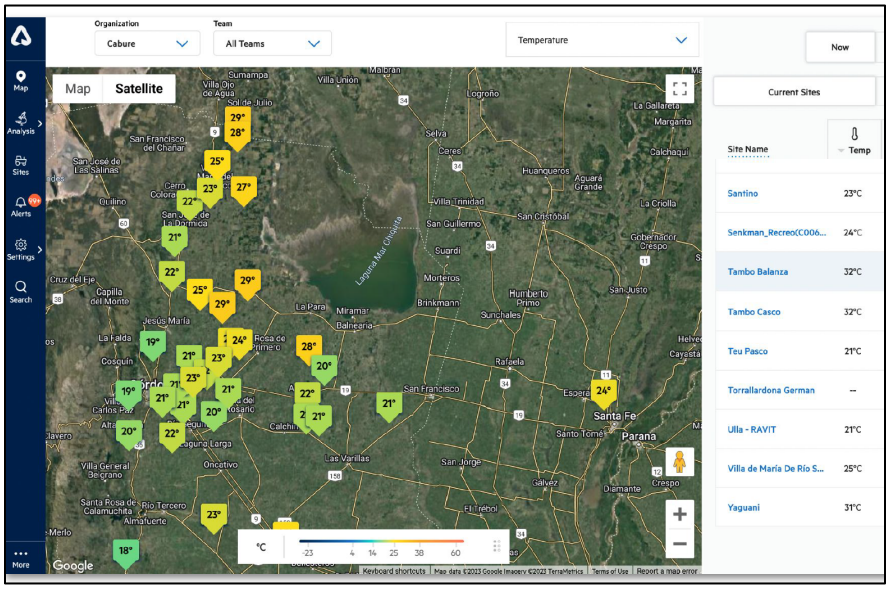
The mobile interface is used immediately after installation to verify that the device is online, synchronized, and transmitting data. It also allows configuration of basic site settings and alert thresholds.

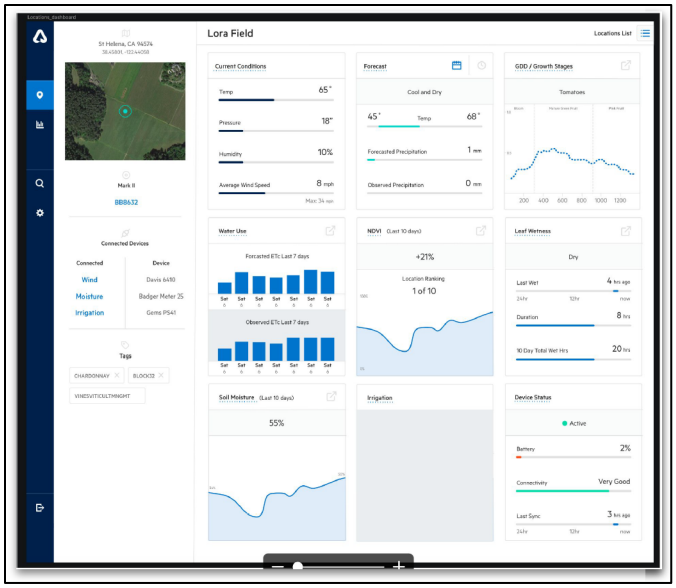
For crop monitoring applications, the crop type – and, where relevant, the crop variety – is selected within the site configuration menu, as illustrated below. Once selected, the platform generates crop-specific indicators automatically based on the recorded environmental variables:



Fleet Monitoring, Data Access and Exploration

6) Data collected by the Arable Mark 2 devices are accessible through both the Arable mobile application and the Arable web platform (https://app.arable.com/auth/). The two interfaces provide comparable functionality, including real-time monitoring of device status (e.g., connectivity and battery level), access to current measurements, and configuration of site settings and alerts. Users can review time-series data, explore historical trends, and compare conditions across locations. The web platform additionally provides a map-based overview of all deployed devices and enables download of time-series datasets in standard formats (e.g., CSV). In addition to manual downloads, the Arable platform provides an Application Programming Interface (API), which enables automated, programmatic retrieval of data (for a detailed explanation of the use of the Arable API, see subsection 4.2 of this technical note). The figures below illustrate examples of the web platform's map-based device overview and data visualization graphs:




Lora Field
Locations List
St Helena, CA 94574
Mark II
BB8632
Connected Devices
Connected
Device
Wind
Davis 6410
Moisture
Badger Meter 25
Irrigation
Gems PS41
Tags
CHARDONNAY
BLOCK13
VINESVITICULTMIGHT
Current Conditions
Temp
65°
Pressure
18"
Humidity
10%
Average Wind Speed
8 mph
Forecast
Cool and Dry
45°
Temp
68°
Forecasted Precipitation
1 mm
Observed Precipitation
0 mm
GDD / Growth Stages
Tomatoes
200
400
600
800
1000
1200
Water Use
Forecasted ETc Last 7 days
Observed ETc Last 7 days
Sat
NDVI (Last 10 days)
+21%
Location Ranking
1 of 10
Leaf Wetness
Dry
Last Wet
4 hrs ago
24hr
12hr
now
Duration
8 hrs
10 Day Total Wet Hrs
20 hrs
Soil Moisture (Last 10 days)
55%
Irrigation
Device Status
Active
Battery
2%
Connectivity
Very Good
Last Sync
3 hrs ago

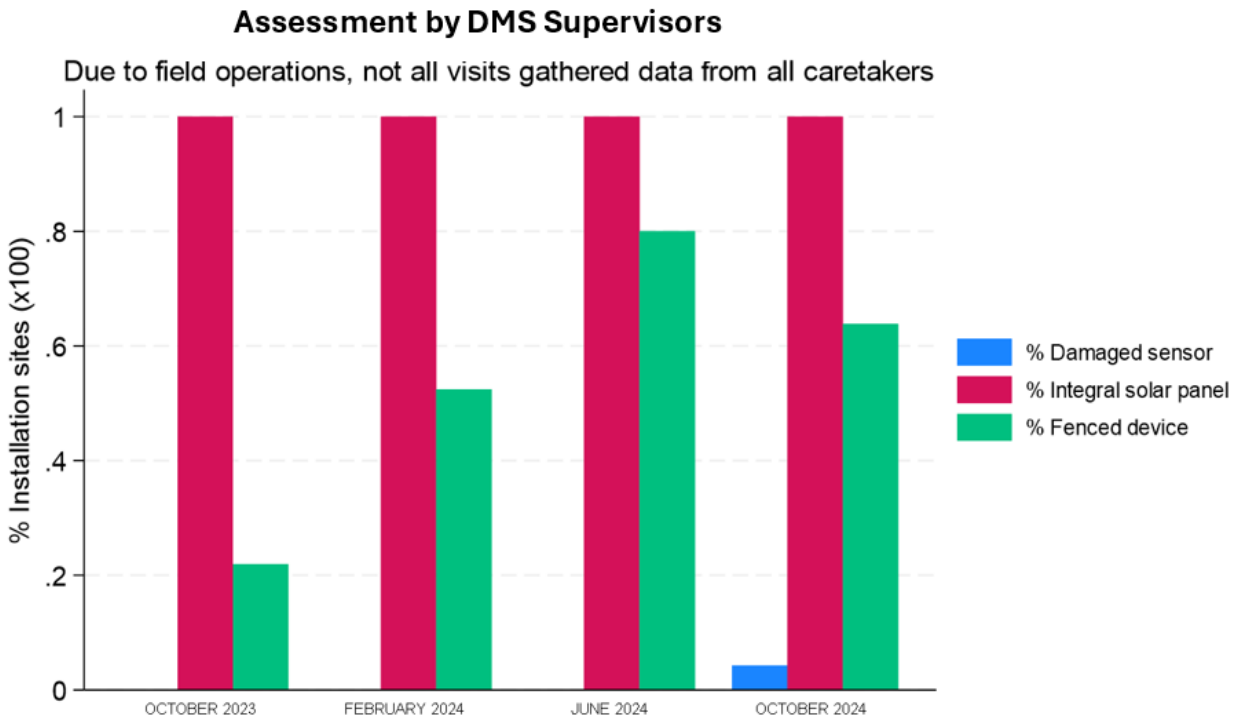
Annex 4. Monitoring Findings from Initial Inspection Rounds of Deployed Weather Sensors in the Uganda CLASS

Summary statistics of basic characteristics of caretakers:

	Mean	N
Female (%)	22	82
Age (years)	48.9	82
Secondary school (%)	46.4	84

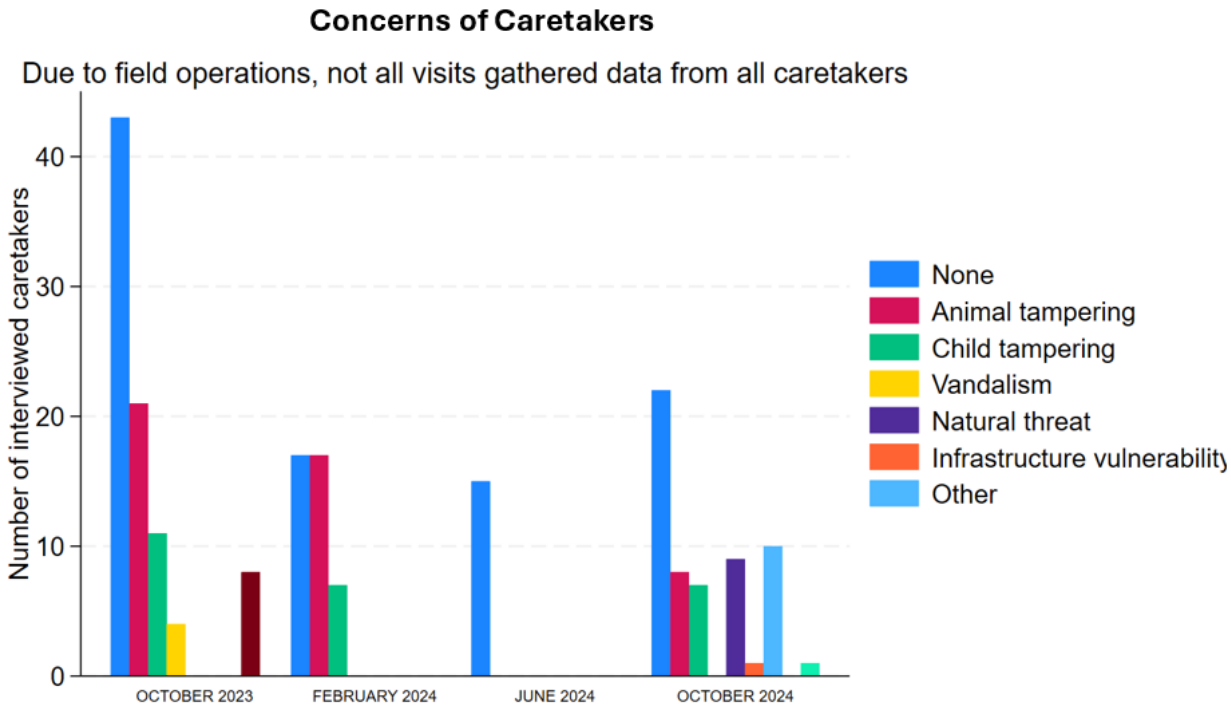
Results from initial field inspection rounds (October 2023, February 2024, June 2024, October 2024):

Figure 3.1. Assessment of issues reported by DMS supervisors.



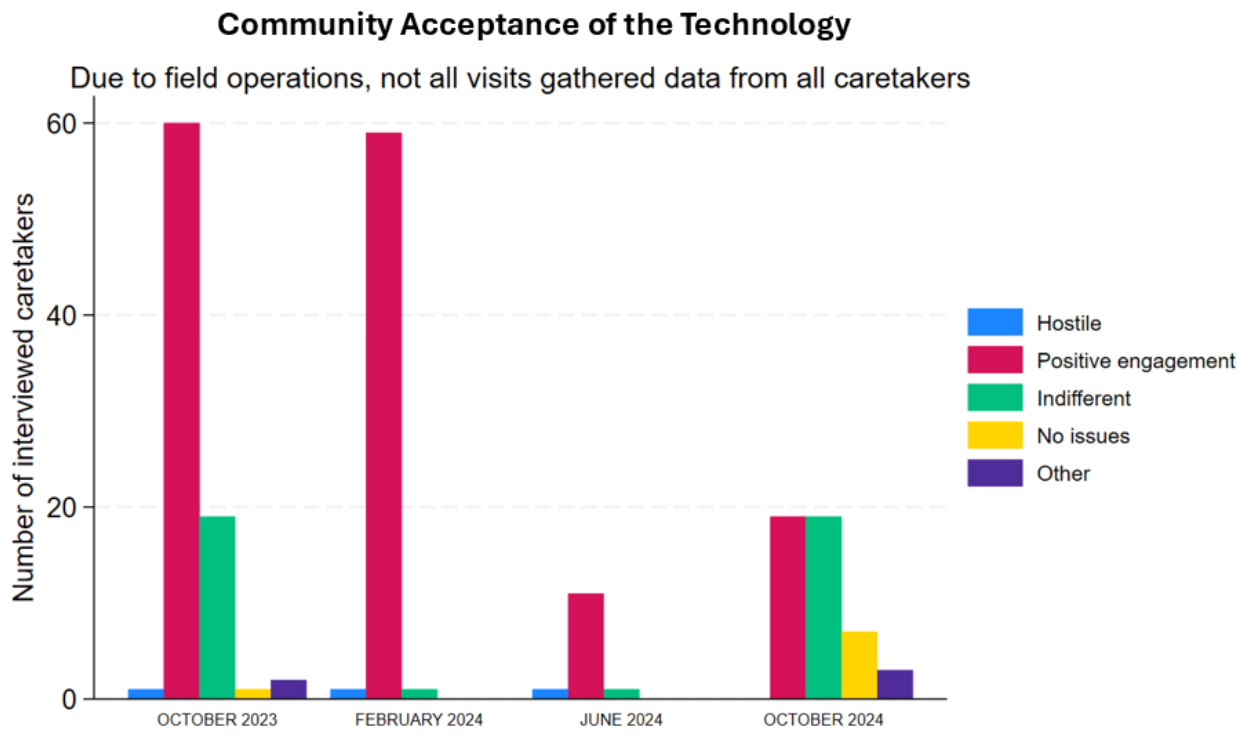
Across all periods, nearly 100% of devices maintained integral solar panels, indicating strong solar panels and no theft issues. However, fencing of devices improved notably from about 23% in October 2023 to over 80% in June 2024, before slightly declining. Damage to sensors remained negligible, with a small increase observed only in October 2024. These results suggest improved site protection over time, though variability in fencing points to operational or maintenance challenges.

Figure 3.2. Device safety concerns reported by caregivers.



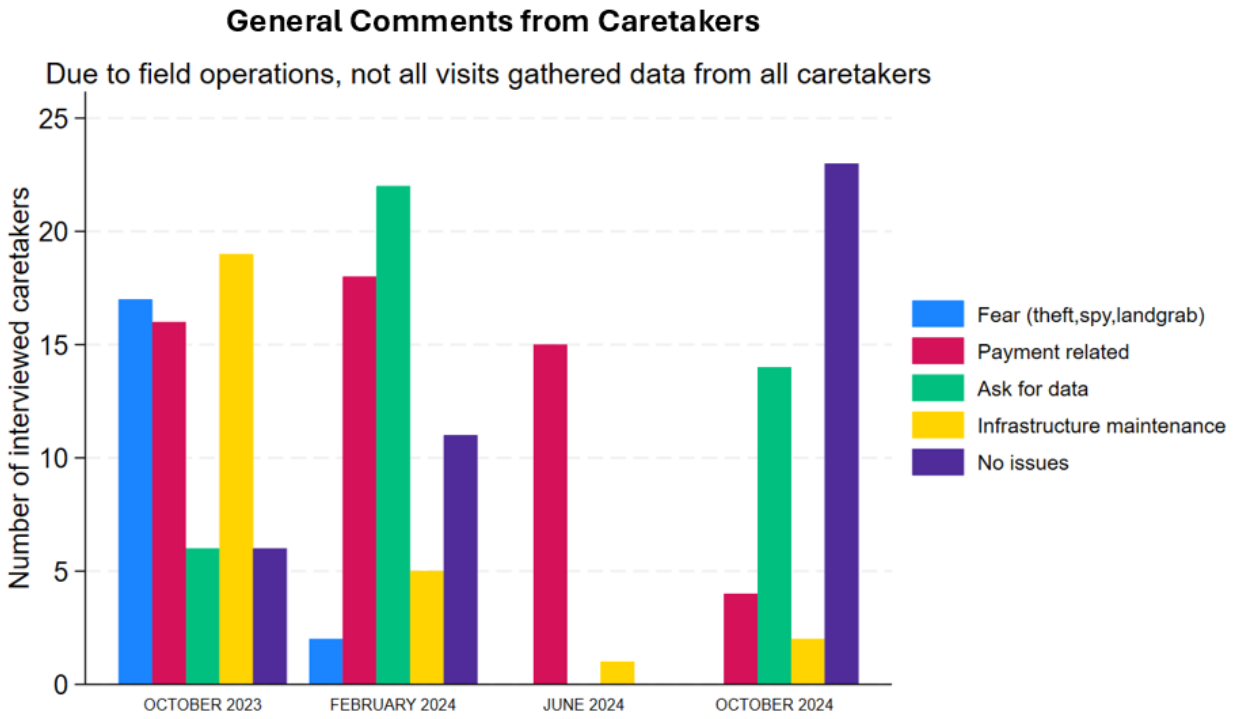
In October 2023, most interviewed caretakers (~43) reported no issues, although significant minorities flagged animal (~21) and child (~11) tampering, with few citing vandalisms. By February 2024, "no concerns" dropped (~17), tampering fears persisted (~17 animal, ~7 child), and a new small group raised infrastructure/fencing vulnerabilities. In June 2024, only "no concerns" (~15) were recorded, implying either fewer interviews or minimal reported problems midyear. By October 2024, "no concerns" rebounded (~22), but a broader range of issues emerged: animal (~8) and child (~7) tampering remained, natural threats (~9) such as pests or weather effects appeared, and miscellaneous "other" concerns (~10) surfaced, alongside a few infrastructure flags. Overall, initial tampering fears gave way to occasional structural worries and later diversified into broader environmental and miscellaneous issues, reflecting changing conditions or heightened awareness over time.

Figure 3.3. Community acceptance of the technology as reported by caretakers.



Over the four follow-up visits, community acceptance feedback shifted noticeably. In October 2023, overwhelmingly positive engagement (~60 caretakers) dominated, with a smaller group indifferent (~19), very few reporting no issues explicitly (~1), and minimal hostile (1) or "other" remarks (2). February 2024 mirrored this: around 59 positive engagements, one indifferent, and one hostile, with negligible "no issues" or other feedback. By June 2024, positive engagement dropped sharply to about 11, alongside a lone indifferent and one hostile response, indicating mid-year fewer active affirmations. In October 2024, acceptance diversified: positive engagement rebounded modestly (19), but indifference rose equally (19), a new cluster (7) explicitly reported "no issues," and "other" feedback appeared (3), while hostile feedback waned.

Figure 3.4. General comments made by caretakers to DMS team.



Over the four visits, general feedback from UNMA/caretakers changed significantly. Initially (October 2023), infrastructure maintenance was prominent (21), alongside notable concerns about payment (16) and fear-related issues such as theft or land grabbing (14), with fewer caretakers explicitly reporting "no issues" (6). By February 2024, requests for data dominated (22), payment concerns persisted (18), while fear sharply declined (2). Infrastructure concerns dropped considerably (6), and caretakers reporting no issues moderately increased (11). In June 2024, responses were sparse, dominated by payment issues (13) and modest no-issue reporting (7). By October 2024, the pattern shifted dramatically: most caretakers reported "no issues" (23), accompanied by significant data requests (14), minimal infrastructure maintenance (2), and fewer payment concerns (4), suggesting stabilization of conditions, increased satisfaction, and heightened interest in accessing data and insights from the device.