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An underground, wireless, open-source, low-cost system for monitoring oxygen, temperature, and soil moisture

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Abstract. The use of wireless sensor networks in the measurement of soil parameters represents one of the least invasive
10 methods available to date. Wireless sensors pose the least disturbance to soil structure and having fewer aboveground cables
reduce the risk of undesired equipment damage and potential data loss. However, implementing wireless sensor networks in
field studies usually requires advanced and costly engineering knowledge. This study presents a new underground, wireless,
open-source, low-cost system for monitoring soil oxygen, temperature, and soil moisture. The process of system design,
assembly, programming, deployment, and power management is presented. The system can be left underground for several
15 years without the need for changing the battery. Emphasis was given on modularity so that it can be easily duplicated or
changed if needed, and deployed without previous engineering knowledge. Data from this type of system have a wide range
of applications, including precision agriculture and high-resolution modelling.

1 Introduction

A remaining challenge in vadose zone monitoring is the measurement of soil parameters, such as water content, with the least
20 disturbance to soil structure. The standard setting of using cables to connect underground sensors to an aboveground datalogger
and power source can change soil structure by causing macro-pores and fractures. The altered structure can potentially cause
unwanted experimental artifacts, such as preferential water flow or higher aeration rates. Also, aboveground cables can be
subjective to undesired damage resulting from weather events, agricultural machinery, pests, and animals (Hardie and Hoyle,
2019; Vuran et al., 2018). The use of wireless underground sensor networks (WUSNs), instead of cables, can solve these issues
25 (Cardell-Oliver et al., 2019; Zhang et al., 2017).

While aboveground wireless sensor networks (WSNs) have been readily studied and implemented (García et al., 2021; DeBell
et al., 2019), the use of WUSNs is still in its early stages (Wan et al., 2017; Hardie and Hoyle, 2019). A WUSN is defined as
a system in which all sensors and communication components are buried underground (node) while wirelessly transmitting
data through the soil to an aboveground hub (also referred to in the literature as a gateway) (Huang et al., 2020). The definition

30   of an underground node is study-dependent, here a node is defined as a single transmitting system located at a single depth; different sensors can be connected to one node via underground cables. The most basic WUSN configuration includes a single underground node and an aboveground hub. Advanced WUSNs can consist of several underground nodes connected to a single aboveground hub (Liedmann and Wietfeld, 2017; Tiusanen, 2013) or a wide-area network combining multiple underground nodes with multiple aboveground hubs (Froiz-Míguez et al., 2020).

35   Ritsema et al. (2009) were the first to monitor soil moisture in a golf course over several km^2 using a WUSN consisting of multiple locations. They used a complex array of 18 underground nodes, each installed at 0.1 m below soil surface, and a single aboveground hub. To bridge the distance between underground nodes and the single aboveground hub, they installed 24 additional aboveground nodes. Private engineering companies provided the network architecture (hardware and software), and no further information was provided to allow reproducibility. More recently, Zhang et al. (Zhang et al., 2017) presented the

40   Thoreau network as the first long-term WUSN for agricultural and environmental sensing. The network consists of a single hub installed at 41 m aboveground, which receives data from 27 underground nodes. Each node was buried at ~0.3 m while connected to soil moisture and water potential sensors. Using a wireless network named Sigfox (902 MHz radio band), they successfully covered an urban area of 2.5 km^2. Although some details on network architecture and power management were provided, there was no detailed description of their customized hardware and software.

45   The extensive development of Internet of Things (IoT) hardware and IoT-related wireless communication protocols provides new opportunities for implementing communication solutions for WUSNs (Salam and Raza, 2020). García et al. (2020) and Vuran et al. (2018) present a comprehensive review of the most utilized wireless communication protocols, including Bluetooth, cellular, Wi-Fi, Sigfox, and ZigBee. Out of which, one of the most suitable for WUSN is the low-power long-range (LoRa) network protocol (referred to here as LoRa-WUSN). LoRa is a relatively new, open technology designed for small

50   data rates up to 50 kbps (Abrardo and Pozzebon, 2019; García et al., 2020) over aboveground distances of 10+ km assuming a clear line of sight (Sanchez-Iborra et al., 2018). LoRa-based networks have recently attracted increasing attention from academia and industry (Fraga-Lamas et al., 2019; Froiz-Míguez et al., 2020). Yet, most studies and implementations were done for aboveground LoRa networks, and LoRa-WUSN is considered an innovative field of research (Liedmann and Wietfeld, 2017) with scarce literature support to date.

55   Radio signal attenuation is a primary consideration for any type of WUSN, with the total attenuation strongly dependent on the length of the signal path in the soil (Bogena et al., 2009). According to Tiusanen (2013), there are four components affecting the signal attenuation between an underground node and an aboveground hub: signal loss due to soil medium attenuation, due to partial reflection from the soil surface, due to angular defocusing, and free air path loss. The first two components are associated with the soil medium and the two latter with the air above. Signal quality, defined by the received signal strength

60   index (RSSI; expressed using negative dBm units, closer to zero means greater signal strength) and signal-to-noise ratio (SNR; positive values indicate more signal than noise), primarily depend on the transmitter operating frequency, burial depth,

transmitter power, distance between the underground node and the aboveground hub, antenna type, data rate, soil moisture, and to a lesser extent on the soil texture and electrical conductivity (Bogena et al., 2009; Hardie and Hoyle, 2019). The limit of acceptable RSSI for wireless communication is subjective and determined based on experimental needs and the RSSI to

65 SNR ratio (Hardie and Hoyle, 2019).

Alongside the advances made in IoT-related wireless communication, open-source hardware is an additional emerging field of interest in environmental research (Froiz-Míguez et al., 2020; Fisher and Gould, 2012; Concialdi et al., 2020). Open-source hardware consists of electronics that can be freely replicated or assembled using openly available instructions, such as schematics, drawings, and layouts (Chan et al., 2020). Arduino microcontrollers and Raspberry Pi microcomputers, with their

70 software platforms, are perhaps the most common examples of open-source hardware. The widespread adoption of open-source hardware is led by hobbyists and the public and to a lesser extent by the academic community (e.g., the OPEnS Lab, Oregon State University). However, the available online information of tutorials, forums, and ongoing developments minimizes the learning curve and can help bridge the gap toward a higher implementation rate of open-source hardware in academic research (e.g., Levintal et al., 2020; Reck et al., 2019; Weissman et al., 2020). Additional benefits of utilizing open-

75 source hardware are: no prior experience with electronics or coding is needed though it can help (Chan et al., 2020), lower costs than existing commercial hardware (Levintal et al., 2021), and the option for customized solutions. Specifically, harnessing open-source hardware for LoRa-WUSN lowers such sensor networks' cost and complexity, thus making them accessible for researchers.

The use of LoRa-WUSN in soil studies has not been comprehensively investigated (Hardie and Hoyle, 2019). The majority of

80 studies on LoRa-WUSN can be found in engineering disciplines and focus on in-soil signal propagation (Wan et al., 2017) and antenna optimization (Salam and Raza, 2020), making it challenging to adapt their conclusions to other disciplines, such as hydrology and soil science. Moreover, there is a lack of studies showing the performance of LoRa-WUSN for long-term measurements (Cardell-Oliver et al., 2019). Most studies previously published on LoRa-WUSN are either proof-of-concept studies or short-lived laboratory experiments (e.g., Huang et al., 2020; Wan et al., 2017). In addition, to the best of our

85 knowledge, there is only one study published to date that tested and presented results from LoRa-WUSN for soil measurements (Cardell-Oliver et al., 2019). None of the aforementioned studies, however, focused on providing step-by-step instructions for the design, assembly, and installation of WUSN by the end-user. Despite the rapid technological advancement of WUSNs, it seems the technology itself (assembly, programming) remains a major challenge to utilizing WUSNs more widely in environmental and academic research. By sharing detailed instructions on the design, assembly and installation of WUSNs,

90 we think these systems can be more widely used by other scientists and adapted to individual research needs.

The aim of this study is to present a new open-source, low-cost, LoRa-WUSN system for measuring soil moisture and oxygen levels at multiple depths in an agricultural soil and to provide in detail the technical information for the system design, assembly, programming, deployment, power management, and data analysis so that other researchers can adapt the system to

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their needs. Emphasis is given on modularity to allow the end-user to duplicate or change, if needed, and deploy without

95 previous engineering knowledge. Therefore, hardware was limited to readily available components only. Eight sensors consisting of four digital soil moisture sensors and four analog oxygen sensors were connected to an underground open-source LoRa transmitter node, and an aboveground LoRa hub logged the received data. For validation, the system was deployed in a field planted with young poplar trees (*Populus trichocarpa*) for five months.

2 Materials and Methods

100 **2.1 Hardware**

Hardware was limited to readily purchasable products in order to assemble a low-cost LoRa-WUSN that can be easily replicated. The LoRa-WUSN installed in the field included two segments: a single underground node (to which the sensors were connected via underground cables) and a single aboveground hub combined with a datalogger (**Fig. 1**). **Table 1** summarizes the details of each sub-segment component. The core of the LoRa-WUSN is the Adafruit Feather M0 with RFM95

105 LoRa Radio (Adafruit, USA), hereafter called LoRa-Feather, which utilized a non-licensed 900 MHz radio band (or a 433 MHz in Europe). This is an open-source microcontroller with an embedded LoRa radio module, which is light and affordable (~$35). It also has multiple general-purpose input/output (GPIO) ports enabling connections to analog and digital sensors, and low power requirements (~0.7 mA standby, ~120 mA peak during 23 dBm transmission) (DeBell et al., 2019). The LoRa-Feather transmission power ranges between 5 and 23 dBm depending on the user choice; dBm (decibel-milliwatts) is the unit

110 used for measuring transmission power output (Parri et al., 2019). We chose this model over other available LoRa-based microcontrollers because of three reasons: (1) the LoRa-Feather has a large set of free online tutorials and supporting information, making the development and integration relatively easy; (2) the LoRa-Feather was previously validated in aboveground LoRa-based experiments (DeBell et al., 2019); and (3) the Feather microcontroller has multiple extension boards (named FeatherWings) that can be mounted on the Feather, thus providing versatile capabilities, such as data logging, without

115 additional hardware complexity.

The underground node (**Fig. 1c**) included a LoRa-Feather connected to an external omnidirectional antenna (900 Mhz Antenna Kit, Adafruit, USA) and a battery (Lithium-ion cylindrical battery - 3.7V 2200 mAh, Adafruit, USA). A power relay extension board was mounted on the LoRa-Feather to optimize the sensors' power consumption (Adafruit Non-Latching Mini Relay FeatherWing, Adafruit, USA). The relay provides power to four digital soil moisture sensors (5TM, METER Group, USA)

120 and to an analog-to-digital converter (ADC) (ADS1015 12-Bit ADC, Adafruit, USA). The ADC was used to convert the data from four analog oxygen sensors (KE-25 Figaro Engineering Inc., Japan). We choose the Decagon 5TM combined soil moisture and temperature sensor and the Figaro KE-25 oxygen sensor due to their low-power requirements (5TM – 0.03 and 3 mA during sleep mode and measurement, respectively; KE-25 – no external power supply required for sensor operation), low cost, and long-term use in soil monitoring (Turcu et al., 2005; Oroza et al., 2018; Weitzman and Kaye, 2017). All

125 components, excluding the antenna and sensors, were placed in a waterproof enclosure and sealed using rubber coating (Performix 12213, Plasti Dip International, USA) to protect against expected soil water (**Fig. 1c**).

Underground nodes for WUSN need to be highly energy-efficient because the battery cannot be recharged without excavation (Hardie and Hoyle, 2019). To reduce the underground node's power consumption, which in our case measured and transmitted sensor data every 1 or 2-hr depending on scenario tested, we used two independent methods. The first method was putting the

130 LoRa-Feather into a low power consumption sleep mode. During the sleep mode, tested power requirements were reduced from ~40 mA during normal active mode or ~120 mA during peak transmission to ~0.035 mA, which translates to about seven years of LoRa-Feather operation using a 2200 mAh battery. However, this is a theoretical calculation because the sleep mode is deactivated during sensor measurements and data transmission and reception. The second method utilized the power relay to eliminate the standby power draw from the four soil moisture sensors and the ADC (to which the four oxygen sensors were

135 connected). The relay was closed (i.e., no power) during sleep mode and transmission/reception and turned on in each cycle for 5 s to allow sensor readings.

The aboveground hub (**Fig. 1b**) includes a LoRa-Feather connected to an external omnidirectional antenna (900Mhz Antenna Kit, Adafruit, USA) and a battery (Lithium-ion polymer battery - 3.7V 1200 mAh, Adafruit, USA). Received data were logged on an SD card using an extension board mounted on the LoRa-Feather (Adalogger FeatherWing - RTC + SD, Adafruit, USA).

140 The lithium battery can maintain only several days of continuous hub operation. Therefore, an external solar panel and a 12 V battery were connected to the built-in lithium battery charging module in the LoRa-Feather. Because the battery provided 12 V, a voltage converter to 5 V was used between the 12 V battery and the LoRa-Feather (UBEC DC/DC Step-Down Converter, Adafruit, USA). All components, excluding the antenna and solar panel, were placed in a waterproof enclosure (**Fig. 1b**).

The total cost of the system, apart from the sensors and solar panel, was $150 (**Table 1**). The sensors cost amounted to ~$1,050

145 for the four 5TM and four KE-25 sensors, yet this can vary depending on the number of sensors needed. In general, there is no limitation on the number of sensors connected to one underground node because the modular nature of open-source hardware allows the addition of hardware according to the user's needs. For example, adding four oxygen sensors can be achieved by adding a second ADC ($10, see **Table 1**) to the underground LoRa-Feather. However, more sensors will, of course, affect the battery life.

150 Detailed assembly instructions for the underground node, sensors, and aboveground hub are provided in the Supplement Information (Section S1).
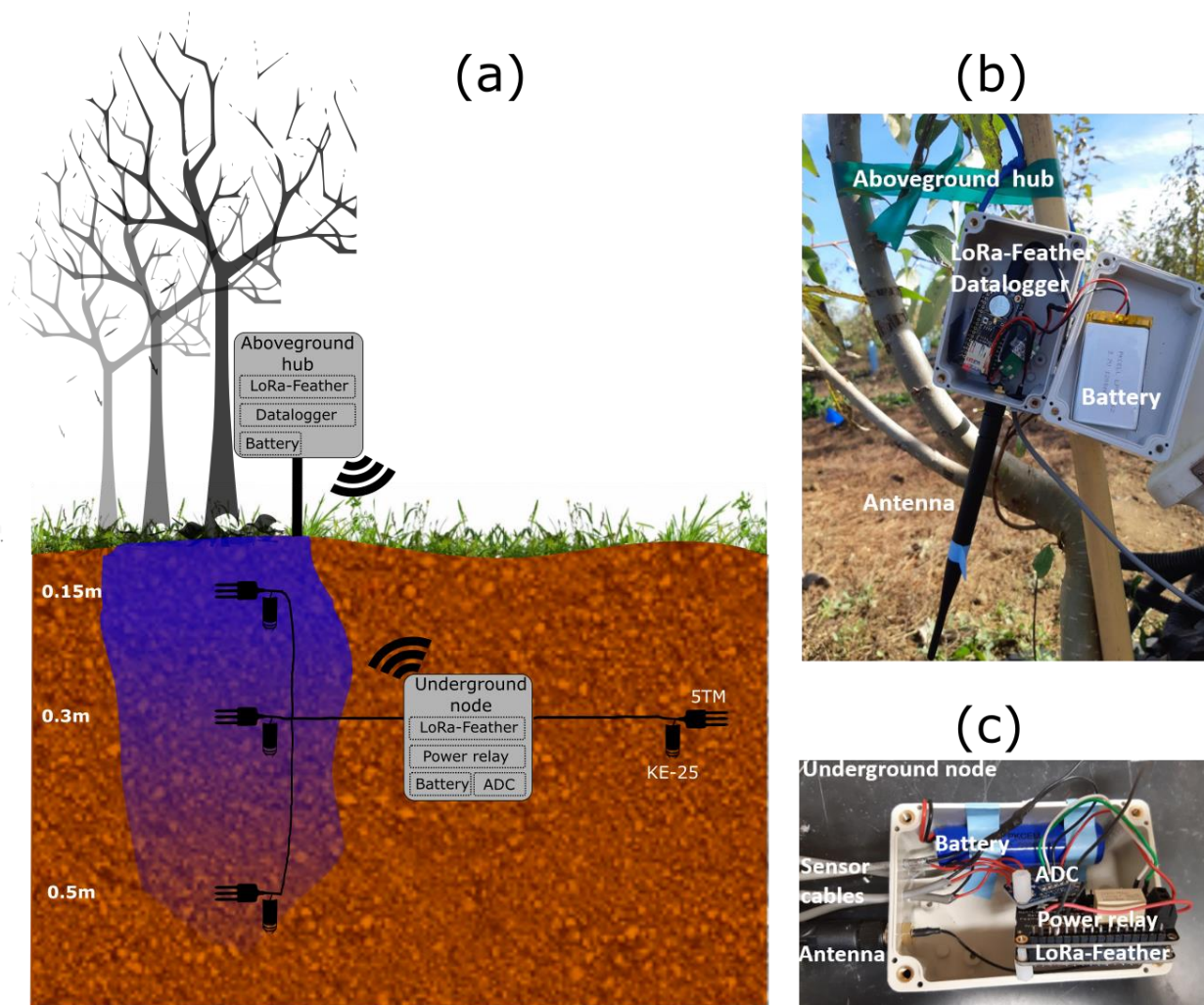
Figure 1: **Scheme of the LoRa-WUSN experimental setup in the field (a), the components of the aboveground hub (b), and the underground node before coating (c).**

155   **Table 1: Summary of hardware components and materials used in this study**.

Component	Cost $	Source of materials	Comments
Underground node			
Adafruit Feather M0 with RFM95 LoRa Radio - 900MHz – RadioFruit	34.95	Adafruit	Depending on the local regulation, use the 900MHz (e.g., USA) or the 433 MHz radio version (e.g., Europe) – both versions have similar capabilities and prices.

Header Kit for Feather - 12-pin and 16-pin Female Header Set	0.95	Adafruit	
900Mhz Antenna Kit - For LoPy, LoRa, etc	12.75	Adafruit	
uFL SMT Antenna Connector	0.75	Adafruit	
Adafruit Non-Latching Mini Power Relay FeatherWing	7.95	Adafruit	
ADS1015 12-Bit ADC - 4 Channel with Programmable Gain Amplifier	9.95	Adafruit	For the four oxygen sensors
Short Feather Male Headers - 12-pin and 16-pin Male Header Set	0.5	Adafruit	
Lithium-Ion Cylindrical Battery - 3.7V 2200mAh	9.95	Adafruit	
LeMotech Waterproof Dustproof IP65 ABS Plastic Junction Box Universal Electric Project Enclosure Pale Gray 3.9 x 2.7 x 2 inch (100 x 68 x 50 mm)	6.99	Amazon	
Sensors			
KE-25 (oxygen sensor)	~60 per sensor	Figaro	Four sensors were used ($240)
50 mL Conical Centrifuge Tubes	~1 per unit	Common lab equipment	Used to protect the KE-25 sensors
5TM (soil moisture sensor)	~200 per sensor	METER	Four sensors were used ($800)
Stereo Jack to Pigtail Probe Adapter, Brown and Orange	~7 per unit	METER	For the 5TM sensors
Aboveground hub			
Adafruit Feather M0 with RFM95 LoRa Radio - 900MHz – RadioFruit	34.95	Adafruit	Depending on the local regulation, use the 900MHz (e.g., USA) or the 433 MHz radio version (e.g., Europe) – both versions are with similar capabilities and prices.
Header Kit for Feather - 12-pin and 16-pin Female Header Set	0.95	Adafruit	
900Mhz Antenna Kit - For LoPy, LoRa, etc	12.75	Adafruit	
uFL SMT Antenna Connector	0.75	Adafruit	
Adalogger FeatherWing - RTC + SD Add-on For All Feather Boards	8.95	Adafruit	
CR1220 12mm Diameter - 3V Lithium Coin Cell Battery - CR1220	0.95	Adafruit	For the RTC of the Adalogger
SD/MicroSD Memory Card (8 GB SDHC)	9.95	Adafruit	
Short Feather Male Headers - 12-pin and 16-pin Male Header Set	0.5	Adafruit	

Lithium-Ion Polymer Battery - 3.7V 1200mAh	9.95	Adafruit	
UBEC DC/DC Step-Down (Buck) Converter - 5V @ 3A output	9.95	Adafruit	
LeMotech Waterproof Dustproof IP65 ABS Plastic Junction Box Universal Electric Project Enclosure Pale Gray 3.9 x 2.7 x 2 inch (100 x 68 x 50 mm)	6.99	Amazon	
12V waterproof solar panel	59.95	Amazon	The solar panel and battery used in this study were used for different experiments simultaneously, and they provided more power than was needed for the LoRa-WUSN. Cheaper options with instructions can be found on the Adafruit web page.
12V battery	18.99	Amazon	

2.2 Software

The LoRa-Feather microcontrollers were programmed using C++ in the commonly used open-source Arduino integrated development environment (Chan et al., 2020). Existing Arduino compatible libraries were utilized and combined to configure

160 and program the overall setup. The complete codes, with libraries and open license conditions, are described in the Supplement Information (section S2) and on Github at https://github.com/levintal/LoRaSystemForSoils. **Figs. 2a** and **2b** present the algorithm flow chart for the underground node and aboveground hub, respectively.

Every measurement cycle conducted by the underground node included 5 s of sensor readings followed by the transmission of four data packets. Splitting the data into four packets was necessary because each packet is constrained to twenty chars (a char

165 is a data type used in C++). The four packets included the measured data from the four oxygen and the four soil moisture sensors, and the node's measured battery voltage. An identifier value was assigned at the start of each data packet to mark its packet index (i.e., 1, 2, 3, or 4). After the transmission of the four data packets, the underground node waits for instructions from the aboveground hub on a new measurement interval or transmission power for the node's next measurement cycle. If such a reply was received, then the node parameters were adjusted accordingly, e.g., increasing the next cycle transmission

170 power from 5 to 23 dBm for cases in which stronger transmission power is needed. After each cycle, the underground node is set back to sleep mode.

The aboveground hub stays constantly in the receiver mode. At the end of a receiving cycle, once the four data packets from the underground node are received, the aboveground hub will send a reply to the underground node with instructions on the new measurement interval or new transmission power, before data packets are written onto the SD card, together with the

175 RSSI, SNR, and a timestamp. If no reply was sent from the aboveground hub to the underground node, then the node will use
its current measurement interval and transmission power for the next cycle.
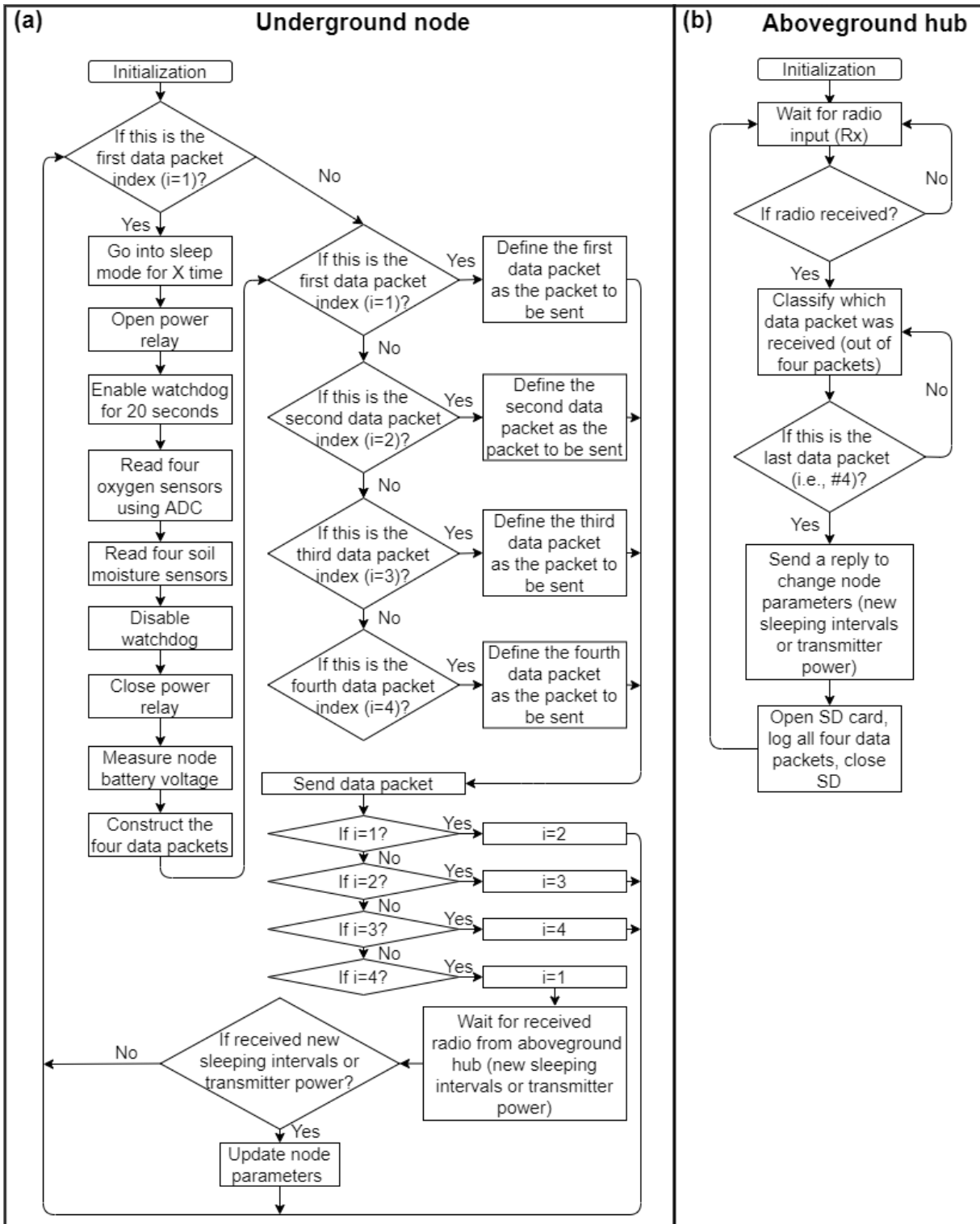
Figure 2: Flow chart for underground node (a) and aboveground hub (b). A description for each step is given within the code (Supplement Information, Section S2).

180 **2.3 Field deployment**

A field experiment was conducted to validate the proposed LoRa-WUSN (**Fig. 1a**). The system was installed in a poplar orchard irrigated with surface drip, located near Davis, CA, USA. The soil type at the site is a Reiff very fine sandy loam (SoilWeb), and the climate is Mediterranean with a total annual precipitation of about 500 mm and a mean annual temperature of 16.9 °C (Kourakos et al., 2019). The underground node was buried at 0.3 m below soil surface between two tree rows with

185 the antenna in a horizontal orientation and pointed toward the aboveground hub, located on a nearby poplar tree at 1 m aboveground (**Fig. 1c**). The horizontal distance between the underground node and the aboveground hub was 2 m. The soil moisture and oxygen sensors were combined into four pairs. Three oxygen/soil moisture pairs were installed below one of the surface drip emitters at 0.15, 0.3, and 0.5 m, and the fourth pair at 0.3 m between the tree rows outside of the drip emitter's effective area. All sensors were connected to the underground node via underground cables buried at 0.3 m. The system was

190 installed and tested throughout the winter season (November-2020 to March-2021). During this season, the soil has elevated soil moisture resulting from winter precipitation, which increases radio signal attenuation. Therefore, the wetter winter season, which is considered more challenging than the drier summer season when using LoRa-WUSN was chosen for this study. Atmospheric measurements were taken from meteorological station number 6 of the California Irrigation Management Information System (CIMIS), situated 1,300 m from the site.

195 To test the performance of the LoRa-WUSN, three experimental scenarios with different sleep modes and signal strengths during data transmission were tested in sequence between November 11, 2020 and Merch 31, 2021. The three scenarios include: (1) 2-hrs measurement intervals and low transmission power of 5 dBm (2-hrs, low transmission power) (11/10/2020-1/7/2021 and 2/27/2021-3/31/2021), (2) 1-hr measurement intervals and low transmission power of 5 dBm (1-hr, low transmission power) (1/8/2021-1/28/2021), and (3) 2-hrs measurement intervals and high transmission power of 23 dBm (2-

200 hrs, high transmission power) (1/29/2021-2/25/2021). In addition to these three scenarios we also tested a 1-min measurement interval and high transmission power of 23 dBm (2/26/2021) to assess the effect of the distance between the aboveground hub and the underground node on the wireless communication signal strength. In this scenario, the aboveground hub was positioned at different distances from the underground node ranging from 1, 10, 20, 30, to 50 m. At each distance, the aboveground hub was measuring for 10 min (1-min intervals) at a constant height of 2 m aboveground with the same antenna orientation. RSSI

205 and SNR values from each location were used to assess communication strength.

3 Results and Discussion

Because the focus of this technical note is on the design and performance of an open-source LoRa-WUSN for measuring soil parameters, our results and discussion will mainly concentrate on the LoRa-WUSN's capabilities, such as battery and wireless communication performance, and not on the interpretation of the actual soil data collected in the field. The field data shown in **Fig. 3** is mainly used to highlight and validate performance aspects of the LoRa-WUSN and to stimulate possible future applications.
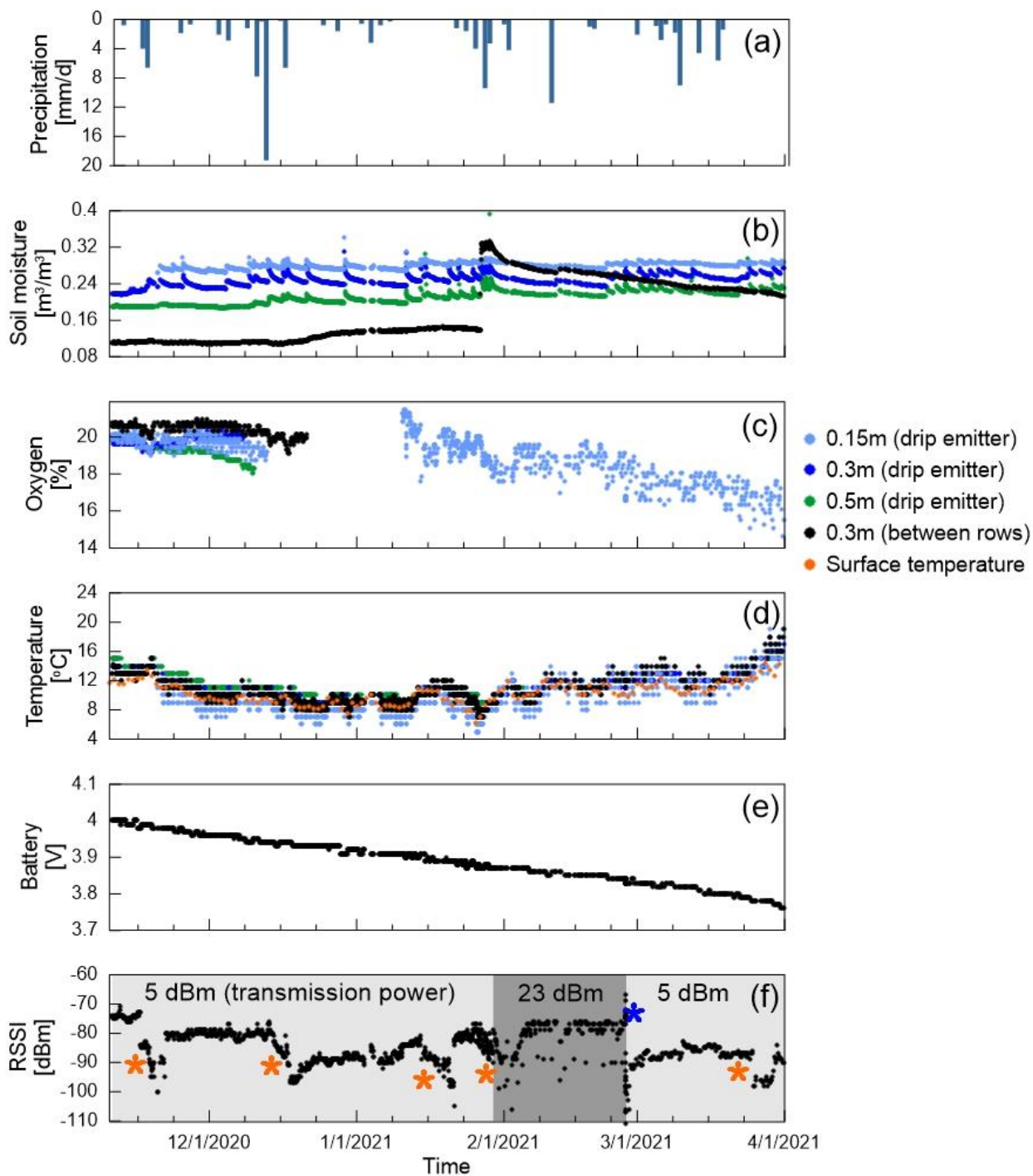
Figure 3: Time series data from the field experiment. Orange asterisks in plot (f) represent the events during which the received signal strength index (RSSI) decreased markedly. The blue asterisk in plot (f) indicates the day of the distance

215 **test (see Fig. 5). Blank areas in plot (c) are periods of missing data due to sensor malfunctions, as explained in section 3.1. The soil moisture sensor at 0.15 m stopped measuring after the initial field installation and was replaced two weeks later.**

3.1 System performance

Soil moisture below the drip emitter (measured with the LoRa-WUSN) increased following each precipitation event and then,
220 after the irrigation was restarted on February 22 2021 (**Fig. 3b,** color lines). Soil moisture between tree rows increased only after major precipitation events in mid-December and at the end of January (**Fig. 3b**, black line). Oxygen concentrations in the soil were approximately 2-5 % lower than atmospheric concentrations with higher concentrations observed in the dry area between the tree rows than below the drip emitter (**Fig. 3c**). A general decrease trend in soil oxygen was observed during periods when soil moisture increased. All four oxygen sensors transmitted very low voltages (1-2 mV) corresponding to 0%
225 soil oxygen content after several weeks of operation. This was likely due to clogging of the sensors' membranes, yet it was unexpected as we used a common sensor type (Kallestad et al., 2008; Turcu et al., 2005). The problem was solved by embedding the sensor in a customized enclosure that contained an additional hydrophobic membrane (PTFE type). The added membrane blocked the water while still allowing gas exchange with the surrounding soil (see enclosure design in the Supplement Information, **Fig. S5**). We note that only the oxygen sensor at 0.15 m below the drip emitter was replaced with a
230 new oxygen sensor and enclosure (1/10/2021) due to limited sensor availability; the clogged sensors were not reused due to the uncertainty regarding their performance and accuracy after clogging. Soil temperatures measured at the shallow depths (0.15 and 0.30 m) showed a typical diel pattern as well as a seasonal trend of decreasing temperatures until the end of January (**Fig. 3d**). Temperatures were stable during February, followed by a sharp increase of ~4 °C during March at all measured depths.

235 The underground node's battery voltage was 4 V at the start of the field experiment and decreased to 3.77 V after five months of continuous operation (**Fig. 3e**). The battery decline rate was linear but varied depending on the measurement interval and transmission power used. **Fig. 4** presents the battery decrease rates for the three main tested scenarios: 2-hrs between measurements with 5 dBm transmission power, 1-hr with 5 dBm transmission, and 2-hrs with 23 dBm transmission. Unexpectedly, the fastest voltage decrease rate was during the 2-hrs intervals with 5 dBm transmission (-0.0021 V/day), and
240 not during the 1-hr intervals or higher transmission power of 23 dBm (-0.002 and -0.0012 V/day, respectively). This was most likely due to the increase in soil temperature at 0.3 m below soil surface during this measurement period (March), which was 3-4 °C higher than during the other scenarios (**Fig. 4**). In general, the amount of self-discharge of lithium-ion batteries is temperature-dependent with higher discharge rates observed at increased temperature.
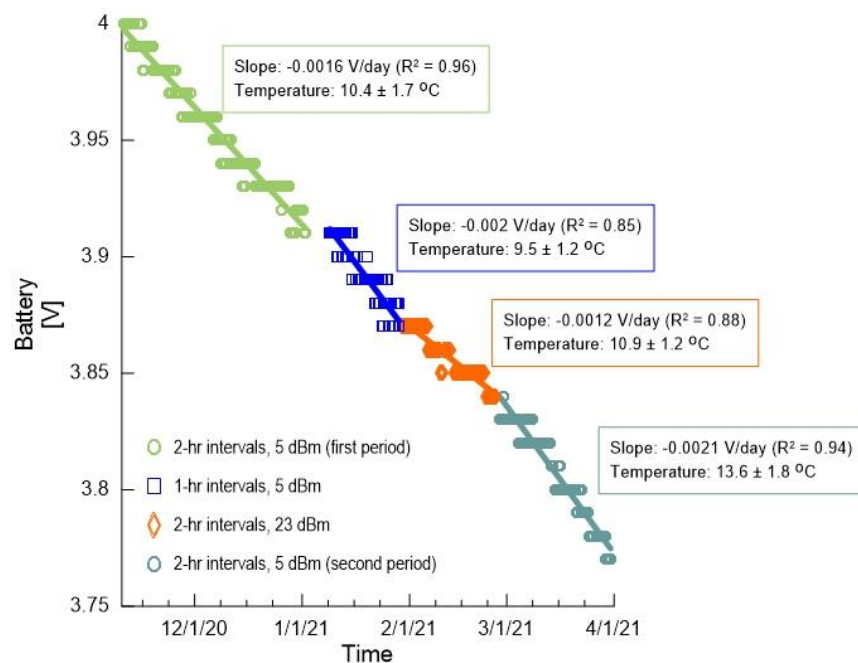
Figure 4: Decrease rate of the underground node battery for three operational scenarios. The slopes were calculated using linear regressions (solid lines) and represent the average voltage decrease rate for each scenario. Temperature values represent the average soil temperature surrounding the node at 0.3 m below soil surface during that specific scenario.

Fitting a linear regression to the battery voltage decrease rate allows estimating a total lifetime of the underground node's battery, assuming a 0.5 V range (i.e., from an initial 4.1 V charged battery to 3.6 V). The average battery decrease rate over the entire experiment was -0.0015 V/day ($R^2 = 0.99$), resulting in a battery life of ~333 days. We note that this estimation also includes the battery's self-discharge during sleep time under an average underground node temperature of 10.4 ± 1.8 °C.

Two power management methods were used in the underground node, a power relay for the sensors (hardware type) and a sleep mode between measurement and transmission cycles (software type). If longer battery life is needed, there are additional power conservation methods available, such as cancelling a data transmission if measured values have not changed above a defined threshold compared to the previous measurement (Tiusanen, 2013), or reducing the number of data packets being sent by implementing an algorithm that reduces overall data size (Cardell-Oliver et al., 2019). Nevertheless, battery prices are relatively low, and therefore, the best solution to extend battery life without complicating the system is to purchase (if needed) a battery with a larger capacity. In our case, replacing the 2200 mAh battery with a 6600 mAh will cost only an additional $20 but will increase the underground battery's life threefold, resulting in 2-3 years of operation.

Average RSSI and SNR throughout the experiment were -84.4 ± 6 and 9.3 ± 0.6 dBm, respectively. Five continuous RSSI decrease events were identified, each lasting several days up to one week (**Fig. 3f**, orange asterisk symbols). Four out of the five events occurred 1-3 days after a major precipitation event (> 5 mm/d). However, the RSSI decrease observed in mid-January occurred after a week with zero precipitation. In general, no significant correlations (using linear regressions) were found between RSSI and precipitation or irrigation pulses or soil moisture at the different depths. Thus, we conclude that precipitation and soil moisture were not the only ambient conditions affecting signal strength. Zhang et al. (2017) came to a similar conclusion which they attributed to the environment's complexity. In other words, the real-world environment compared to lab conditions contains additional undetected parameters apart from soil moisture that reduce RSSI. Increasing transmission power from 5 to 23 dBm (1/29/2021-2/25/2021) improved the signal strength slightly, giving an average RSSI of -81.3 ± 5.7 dBm, which was higher than the average of the following month of March (-87.9 ± 3.5 dBm with low power transmission of 5 dBm). This can also be visually observed by the higher RSSI baseline during the high-power transmission scenarios (23 dBm) compared to the low-power transmission scenarios (5 dBm) (**Fig. 3f**).

The effective communication range between the underground node and aboveground hub was tested for two hours on 2/26/2021. This relatively short period was chosen to ensure similar ambient conditions throughout the test (similar relative humidity, temperature, soil moisture, etc.). The underground node was set to transmit at 1-min intervals and 23 dBm via a command from the aboveground hub. RSSI and SNR decreased with increasing distance between the aboveground hub and the underground node (**Fig. 5**). At the maximum distance tested (50 m), data packages from the underground node were still received and logged with an RSSI and SNR of -108.4 ± 1.7 dBm and 3.3 ± 1.8, respectively. The results agree with a LoRa-WUSN communication range test conducted by Hardie and Hoyle (2019) using an underground node at 0.3 m transmitting at 23 dBm and an aboveground hub. The authors tested LoRa RSSI and SNR results from four different soils (ranging from beach sand to clay loam) at distances ranging from 0 to 200 m. Their results show that even at 100 m, data packets were received by the aboveground hub, suggesting that similar to our setting, a distance greater than the 50 m tested in this study would be feasible if needed.

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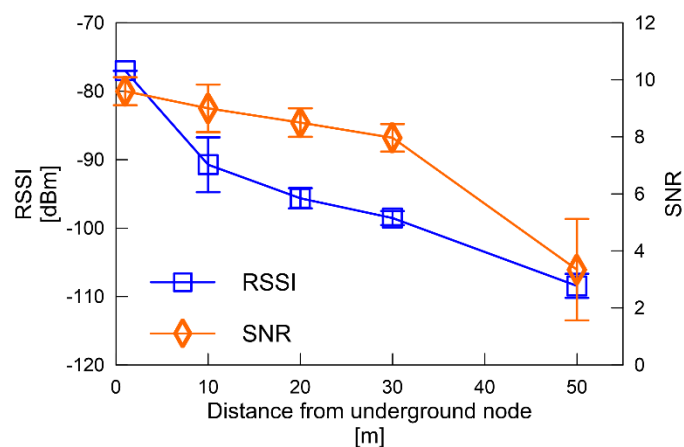
285 **Figure 5: Received signal strength index (RSSI) and signal-to-noise ratio (SNR) as a function of the linear distance between the underground node and the aboveground hub. The aboveground hub was positioned at five distances from the underground node (1, 10, 20, 30, and 50 m). At each distance, the hub recorded one reading per min for 10-min at a constant height of 2 m aboveground with the same antenna orientation. Transmission of the underground node was set to 23 dBm. Error bars indicate the standard deviation from the average of 10 measurements at each distance.**

290 Apart from RSSI and SNR, another critical parameter is the data packets receiving ratio, defined as the number of received data packets at the aboveground hub divided by the packets that were sent from the underground node; a ratio of 100 % represents ideal conditions in which all sent packets were also received at first attempt. The average ratio during the experiment was 75 %, with higher ratio values observed at the start of the winter (~87 % during October) compared to the end (~50 % during February). Lab test, conducted for five days using the same system setting (2-hr intervals, low power transmission of 5 295 dBm) resulted in a data packets receiving ratio of 100 %. By comparing the lab and field results, we conclude that the decrease in received packets was due to electromagnetic interferences at the site. Potential sources of electromagnetic interferences were a nearby active airport situated 500 m to the south and an eddy-covariance flux tower situated at the same experimental site. Even with the low receiving ratio observed in February, the system was still able to transmit and store most of the data received from the underground node measured at the specified intervals. Missing data packets are an acceptable limitation for 300 WUSN (Zhang et al., 2017). However, if needed, there are possible solutions to ensure higher data packet receiving ratios, as discussed in the next section.

3.2 System modifications and configurations

In this study, we present a LoRa-WUSN that was built to measure soil moisture, soil temperature and soil oxygen content. Nevertheless, the modular nature of open-source hardware allows the end-user various options for system configurations 305 without adding substantial complexity. For example, instead of on-site data logging as conducted here, it is possible to add a Wi-Fi component to the aboveground hub to get online real-time data (DeBell et al., 2019). If no Wi-Fi is in range, a cellular modem can replace the Wi-Fi component (Spinelli and Gottesman, 2019), which will be more costly due to the cellular service charges but it would provide greater flexibility and range. An alternative solution is sending the data from the aboveground hub at the experimental site to another aboveground LoRa station situated several kilometers from the site in an area with a 310 Wi-Fi signal or Ethernet connectivity. Combined solutions, such as on-site data logging and Wi-Fi, Ethernet, or cellular communication, are also possible (Levintal et al., 2021).

Installing multiple underground nodes at different locations is also feasible. This requires a simple software modification, in which every data packet (i.e., every singular transmission) is labeled at the start of the packet with another identifier specifying the sending underground node, and accordingly, the aboveground hub knows from which node the packet was received. A

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315 similar method was presented by DeBell et al. (2019) for aboveground LoRa networks. We tested and validated this transmit protocol in the lab using two underground nodes and a single aboveground hub (data not shown).

Embedding a feedback mechanism within the code is possible if a packets receiving-ratio of 100 % is desired (i.e., all the sent data are also logged on the aboveground hub). The underground node continuously sends the same data packet until a reply from the aboveground hub is received stating that the packet was logged. The tradeoff of this modification is the increase in

320 power consumption of the underground node due to the potentially greater number of transmission cycles. Power consumption can be managed within the code by implementing a predefined threshold voltage below which the feedback mechanism will be disabled.

4 Conclusions

This study presents a novel, low-cost wireless underground sensor network (WUSN) for soil monitoring using the relatively

325 new, open communication protocol named low-power long-range (LoRa). A field test, conducted for five months in an agricultural field, allowed assessing the system's capabilities. Soil moisture content, temperature, and soil oxygen concentrations were measured at three depths (0.15, 0.3, and 0.5 m) and data were transmitted from an underground node (0.3 m) to an aboveground receiving and logging hub. Communication tests showed an effective range of at least 50 m is possible between the underground node and aboveground hub. Using power management methods, battery life was estimated at ~333

330 days, with an option to triple this period when using a battery with bigger capacity. The cost of all the data logging, power, and communication components was $150, one or two orders of magnitude smaller than other available commercial solutions. Emphasis was given on providing the complete technical guide and using only readily buyable hardware. By doing so, the technical and cost barriers were reduced, which we hope will allow easier reproducibility and open new applications for vadose zone and environmental monitoring studies.

335 **Data Availability**

The data is available within the above manuscript and the supplementary information.

Author Contributions

EL conceptualized and conducted the study and wrote the first manuscript draft. HED provided the resources. All the authors (EL, YG, GT, PFS, KS, and HED) contributed to the final version.

340 **Acknowledgments**

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