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Making technological innovations accessible to agricultural water management: Design of a low-cost wireless sensor network for drip irrigation monitoring in Tunisia

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ABSTRACT

Unsustainable use of water resources and climate change will exacerbate the existing tensions surrounding resources, especially in the Mediterranean context. Despite investments in costly modern equipment, the performance of irrigated agriculture remains below expectations, notably because of the lack of available water data and the limited use of decision support tools. Although a variety of soil moisture sensors are available on the market, they are not widely used by the agricultural community because of their high cost and complexity. Access to information at an unprecedented level, via easily accessible low-cost and low-tech sensors, may be a major lever for improved identification of achievable gains in performance, and to guide actors toward efficient water management. To explore this hypothesis, an open source wireless soil moisture sensor, low-energy and economically and technically accessible, was developed. The tool was designed according to water users' requirements and applied to a Tunisian irrigation scheme subject to major water use efficiency issues. The functioning of the wireless sensor network was tested on pilot plots over a growing season and compared with commercial sensors. A single parameter calibration can be performed in either the laboratory or the field. This low-cost sensor can be used for real-time irrigation monitoring and as a decision-making tool for water management.

1. Introduction

Irrigation is a fundamental aspect of crop production. Summer 2022, already considered to be one of the driest and warmest seasons ever recorded in Europe and the Mediterranean basin [1], has shown how crucial it can be [2], and what is more, the Mediterranean region is considered as a climate change hotspot. The Intergovernmental Panel on Climate Change [3] foresees the intensification of extreme hydrological events, notably more frequent and longer episodes of water deficit. Agricultural activities, largely dependent on water availability, are particularly impacted and threatened. Irrigation is a response to agricultural vulnerability to drought. As a result, irrigated land has increased in recent decades, and the increase will most probably continue in the future.

However, pressure on water resources is already critical in the Mediterranean region, due not only to the high spatio-temporal variability of its distribution but also to increased urban and rural demand. In particular, agricultural water demand tends to grow with increasing potential evapotranspiration. These tensions have already led to water use restriction policies, user conflicts and water shortages [4]. In this context, it is indispensable to improve agricultural water management and encourage water-saving practices. Precision agriculture has flourished in recent decades and a wide range of monitoring tools including model-based control strategies, automation systems, remote sensing or in field sensing [5,6] have been developed to improve the performance of irrigated systems. At farm level, irrigation management can be supported by using soil moisture probes to improve irrigation scheduling and reduce the volumes applied throughout the growing season [7,8]. Tensiometers and capacitance sensors that provide information on soil water status are already available [9] but are rarely used in farming

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systems, particularly at the farm scale, and even more rarely in the Global South. The different barriers to the adoption of precision farming technologies are linked to the user's socio-technical environment, but mostly to (i) economic rationales or (ii) the complexity of using these technologies, including the calibration procedures [10,11].

Recent technological developments such as onboard electronics and Internet of Things (IoT) offer new opportunities to provide alternative monitoring tools for agro-systems and resource management [12] that are easier for farmers to use than previous systems. For irrigated agriculture in particular, these technologies allow real-time monitoring of water flows through water sensor networks (WSN) that can be installed at the required spatial and temporal scale. Several studies have demonstrated the technical feasibility of monitoring irrigation using these types of systems with different telecommunication networks and sensors to monitor weather, soil and plant variables [13–15]. Some studies mentioned gains in irrigation performance in different agronomic contexts thanks to the use of such tools [16–18]. Recently, some advances were made in the characterisation and calibration of low cost capacitance sensors for IoT networks [19,20]. However, to our knowledge, no study has yet gone beyond laboratory prototypes or experiments in controlled conditions, and have adapted these innovations to local agrarian contexts. The objective of this study was thus to fill this gap by developing a soil moisture sensor that is easily adoptable by water users and to share all the steps, from design to calibration, operation and maintenance, based on a field reality. To this end, we designed an open source, low-tech and low-cost tool with a single parameter and physically-based calibration method, tested it in real farmers' conditions, and assessed the potential advantages and limits of this technology.

2. Material and methods

2.1. Shaping innovation: Our overall approach

We argue that for technological innovations to be useful for end users, the innovations need to be co-developed with the stakeholders thus making it possible to adapt the technology to the local context. A co-innovation process between researchers and stakeholders was established to (i) chose the variable to monitor; (ii) build the sensor and (iii)evaluate its use. This was done through a loop back procedure described in Vandôme et al. [21]. After diagnosing the agrarian context, local water management issues and stakeholder needs, a sensor prototype was submitted to water users through a demonstration workshop. The feedback provided by the workshop participants enabled the production of a second version of the prototype that was better suited to local needs and constraints. The creation of an area for the design, maintenance and sharing between the actors of the co-innovation process – hereafter called Fab Lab – allowed the innovation to continually evolve based on the users' feedback throughout the process.

2.2. Study site and water user requirements

The Echraf public irrigation scheme is located in the Haouaria agricultural plain, at the northern tip of the Cap Bon peninsula in Tunisia (36°59′33.529″N, 11°2′28.309″E). Drip irrigation of market gardening crops grown on sandy and draining soils has resulted in several problems. The reduced soil water holding capacity (around 4%) makes irrigation management complex: on the one hand the permanent wilting point (PWP) is quickly reached due to rapid drying of the soil; while on the other hand, the root profile is quickly saturated during an irrigation event, leading to percolation losses. In these conditions, optimal irrigation would theoretically involve regular application of low water volumes. In practice, this strategy is difficult to achieve for the farmers, due to (i) lack of information concerning the water resource (volumes applied, discharge rates, soil moisture, surface area irrigated), (ii) the variable flow rates of water supplied by the collective network, (iii) poor uniformity of application due to ageing or low quality irrigation equipment, and (iv) the recent emergence of drip irrigation technology in the region, which has not been combined with any training for water users. In the first stages of the co-innovation process, the stakeholders and the researchers agreed that, to solve these problems, a soil moisture sensor – hereafter termed Pilowtech – should be used in the field to assess crop water availability. To further develop this idea, a Fab Lab was set up in the Water Users Association (WUA) building where exchanges with farmers led to a set of specifications (Table 1) that were then used to design prototype soil moisture sensors. The Fab Lab was also used for the production and repair of the sensors. In parallel, three pilot farmers volunteered to host tests of the sensors in real conditions in three irrigated potato plots throughout the whole crop cycle.

2.3. Water sensor network: General framework

In response to the end-users' stated needs, we built a network of wireless, low-cost, low-tech, low-power and open-source soil moisture sensors. The overall architecture of the network of sensors is shown in Fig. 1.

2.3.1. Hardware components

The Pilowtech sensor is composed of a soil moisture probe, a data acquisition module and a power supply. The capacitance soil moisture sensor – model EK1940 v1.2 – was chosen for its resistance to corrosion, its low cost and availability. In addition, it operates over a voltage range of 3.3 V to 5 V, making it compatible with low-power microcontrollers. The data acquisition module includes a microcontroller, a communication microchip and small electronics (wires, resistors, breadboard). The microcontroller chosen was the Arduino Pro-Mini, with a 3.3 V voltage and a frequency of 8 MHz. In addition to the advantages of Arduino systems (widely used, easy to use and open-source), thanks to its small size, the Pro-Mini is easy to embed and is one of the cheapest controllers on the market. It is also compatible with the LoRaWAN (Long-Range Wide-Area Network) communication protocol. The LoRa SX1276 communication module makes it possible to send and receive data via the LoRA radio network. The whole device is powered by a rechargeable Li-ion 18,650 battery (3.7 V and 3500 mAh).

To allow onsite and instantaneous data reading, a reader was further developed based on an Arduino Uno board and a liquid crystal display (LCD) shield. The system is powered by a rechargeable Li-ion power bank with a 3.7 V output. To avoid damage caused by humidity, the probes were assembled at the end of PVC pipes (Ø40). Silicone was used to guarantee a tight sealing at the junction of the probe/pipe and the heat-shrink tubing at the wire junctions. The case of the acquisition module was printed using a 3D printer. The 3D printing file is available in the research data section at the end of this article.

2.3.2. Wireless communication network

IoT technologies allow wireless communication of data generated by devices via different types of networks. The LoRaWAN communication protocol allows data transmission at low data rates (0.3–50 kb/s) and over long ranges ($\leq$ 30 km). Compared to other available networks, the LoRa network stands out for its low energy consumption [22]. The LoRaWAN protocol thus met both our objectives and technological

Table 1
Set of specifications for the development of the water sensor defined during the co-innovation process.

Stakeholder requests and expectations	Practical response
Information on when/how much to irrigate	Soil moisture sensor
Economically accessible to farmers	Low-cost hardware/no cost software
Easy to design, use and maintain	Low-tech and open access
Autonomous	Wireless, low-power
Adapted data reading procedure	Onsite and online data reading
Adapted to different soils	On field calibration method

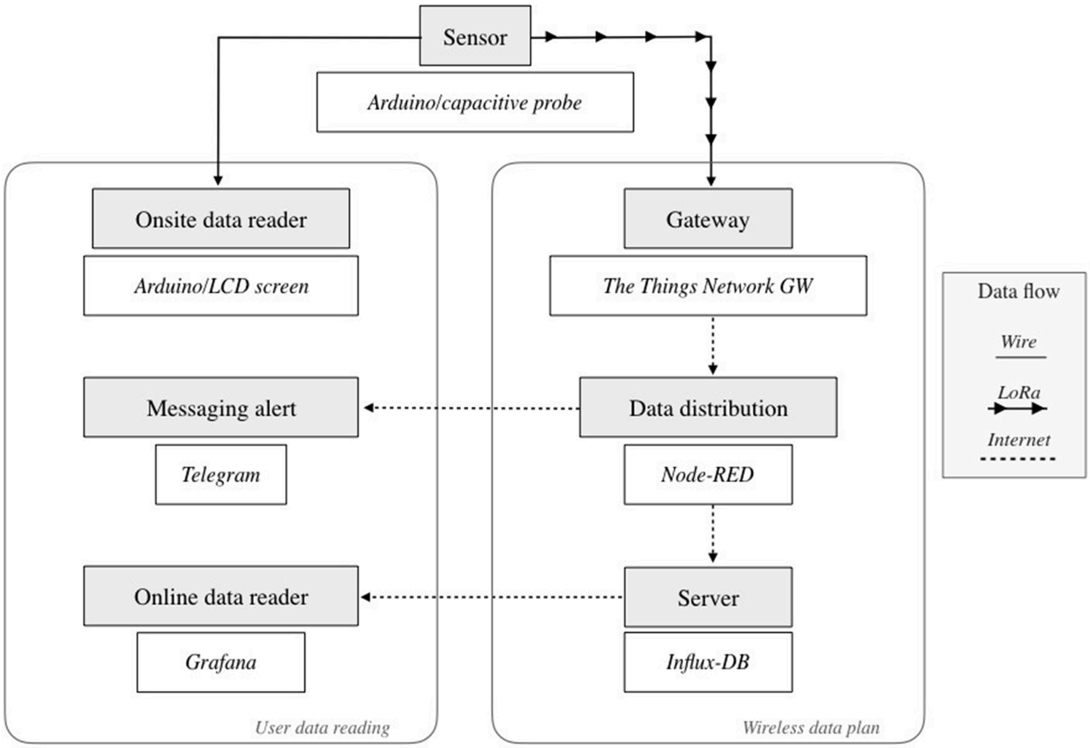

Fig. 1. Flowchart of the water sensor network.

development conditions (sparse plots, no need for heavy data packets) and had also been tested in previous studies [23]. A private LoRa network was set up in the irrigation scheme. Likely due to the topography, two gateways were needed to cover the area that included the three experimental plots. The Things Network gateway, which, according to the manufacturer, has a range of about 10 km, was installed near the Fab Lab. The Things Indoor gateway, which has a shorter range but costs less, was installed between two pilot plots in the eastern part of the irrigation scheme. 4G+ airboxes were used to provide the Wi-Fi required for the gateways internet connection.

2.3.3. *Software and data workflow*

The microcontroller was programmed in C/C++ language using the open source Arduino software (IDE) 1.8.19. The program was uploaded from the computer to the Arduino Pro-mini using a FTDI wire. To minimize energy consumption, the program code was written to maintain the sensor in sleeping mode (low μA consumption). The system woke up at 5-minute intervals to collect the analog signal produced by the probe, to convert it into digital data and send it through the LoRa network. Theoretically, this optimization enables the sensor to be energy autonomous throughout the irrigation season. The Arduino program is also available in the research data section.

The data produced transited locally through the gateway via the LoRa network and was then routed online to the free server "The Things Network Cloud (Europe 1)" [24]. Within this server, the gateway was declared on the cloud and an application gathering sensor (device) IDs was generated. This server allowed real time data reading online but not storage or data processing.

The free and open-source flow-based programming tool Node-RED [25], was thus used to gather the data from this online server and store it on a local server via an InfluxDB database [26]. The Node-RED flow is also available in the research data section.

2.3.4. *User access to data*

Three different types of user access to data were provided through multiple channels to serve end-users with different technology literacy levels: (i) an online platform with access to data time series; (ii) a mobile phone messaging alert system; and (iii) an onsite data reader (Fig. 1). The online data reading is done using Grafana software [27], a free open-source data visualization and processing platform. A dashboard was produced to visualize data from each pilot farm. The dashboard comprised time series graphics for each soil moisture sensor (specified by its location and depth) and a map showing the location of the sensors. Data could be combined for visualization at different levels (plot, farm, irrigation scheme – the highest level being defined by the network). In parallel, Grafana enabled the development of a messaging alert system using the Telegram smartphone application and Telegram bots.

The alert system was set to send a message to the end-user each time the soil water content (i) dropped below a threshold value (permanent wilting point), corresponding to a certain level of crop water-induced stress; or (ii) reached field capacity, in order to stop irrigation. The onsite data reader was designed for instantaneous visualization. The farmer has to physically plug the onsite reader into the sensor to get an instant display on the LCD screen. The reader can be programmed to display the volumetric soil moisture content, or the% refill level of total available soil moisture. Both Arduino programs are available in the research data section.

In all cases, it is necessary to provide the user with data that can be easily used and guide their decision-making. The data emitted by the sensors and stored on the server are raw data, proportional to the output voltage of the capacitance probe. It is therefore necessary to define the relationship between soil moisture and raw values, before processing the data using visualization tools.

2.4. *Calibration of the capacitance probe*

The capacitance probe operates according to the following principle: electric current flows through a coplanar concentric capacitor, which is the part inserted into the soil. The capacity is proportional to the relative dielectric permittivity of the medium, which itself depends on the soil moisture content. The output voltage (0–5 V) is converted into a digital value (10 bits) by the analog-to-digital converter (ADC) of the microcontroller. Two calibration protocols based on the gravimetric method are proposed to determine the relationship between the output voltage and soil moisture.

2.4.1. Calibration in the laboratory

Laboratory experiments allowed us to determine the relationship between the output values of the sensor (ϵ) and the volumetric soil moisture (θ_v,% volume). The gravimetric method was used. Three soil samples (S1, S2, S3) were collected from the 0–30 cm horizon in three separate plots in the irrigation scheme. In parallel, bulk density was measured in each plot using the cylinder method. Samples were first dried in a heating chamber at 105 °C for 24 h and then left to cool at room temperature (20 °C). The dry soil samples were then used to fill a beaker of known volume (150 mL) while making sure the field bulk density was maintained by weighting the beaker. The volumetric humidity (θ_v) could therefore be defined by Eq. (1):

$$\theta_v = \frac{V_w}{V_s} \cdot 100 \quad (1)$$

where θ_v is the volumetric soil moisture content (%), V_w the water volume,

V_s the dry soil volume.

To determine the relationship, the probe was inserted along the entire length of the capacitance device (approximately 6 cm), guaranteeing good contact between the soil and the probe. A small volume of water (1.5 mL corresponding to an increment of 1% of soil volumetric moisture) was repeatedly added to the sample. At each addition, the soil was mixed to guarantee isotropy, left to rest for 15 min and then restored to bulk density. The operation was repeated until the digital value reached a plateau, corresponding to soil water saturation. The digital value of the sensor, ϵ, acquired with the onsite reader, was recorded for each known sample volumetric humidity value, θ_v, in order to establish their correspondence.

2.4.2. Field calibration

The purpose of field calibration was to provide a simple method to locally parametrize the soil moisture sensor without the need for sophisticated equipment. A soil sample was collected from each of the three pilot plots (samples P1, P2 and P3). The protocol was the same as that used in the laboratory with the following adaptations. First, the samples were dried in the sun on the roof for two days, followed by 3 h in an oven at 100 °C. To check the soil was dry, the sample was weighed on a kitchen scale (precision ±1 g), then put back in the oven and weighed again. If the mass of soil was unchanged, the soil was considered to be dry. Second, to limit the uncertainty caused by the use of a simple kitchen scale, a large mass of soil was used and the sample was only weighed at initialization. Bulk density could not be measured in field conditions. Consequently, a standard sandy bulk density was defined for the soil samples (1.5 kg of dry soil for 1 L in a graduated bucket), for which the θ_v-ϵ relationship was established.

Water was progressively added using a 10 mL measuring glass (i.e. an increment of 1% θ_v). Readings were made with the sensor in the same conditions as those used for the laboratory calibration. Three replicates were made for each soil sample using three different probes in order to study the potential variability linked to the capacitance probe and its impact on the calibration.

2.4.3. Properties of the soil samples

Soil samples from the pilot plots were analyzed in the laboratory. Table 2 lists the main soil properties. Despite slight local heterogeneities, the soils had most properties in common. They are sandy soils (≥ 90%) with low organic matter content (≤ 1%). Water storage capacity is low, with permanent wilting points ranging from θ_v 5% to 7% and field capacity ranging from 9% to 11%. Bulk density is about 1.6 g/cm^3.

2.4.4. Field implementation

Soil moisture measurements make it possible to understand different physical processes such as filling of the total available soil moisture, deep percolation, or surface evaporation. The choice of the location and depth of the sensor depends on the properties of the type of soil and the processes to be monitored, as well as the characteristics of the cropping system. In our study site with a drip-irrigated potato crop, the objectives were twofold: to ensure crop water comfort and to limit deep percolation. To this end, soil moisture was measured at two depths: (i) at a depth of 30 cm, at a distance of 15 cm from the drip line, and (ii) at a depth of 60 cm, directly under the drip line. These measurements provided information on the structure of the water bulb. On the one hand, we considered that "correct" soil moisture at the two locations satisfies crop water comfort and on the other hand, that high soil moisture content at a depth of 60 cm – the maximum effective rooting depth – leads to deep percolation. Field monitoring lasted from March 5 to June 15, 2022. Three plots were instrumented with two to three Pilowtech sensors each, corresponding to approximately one sensor/0.1 ha.

To evaluate the quality of the sensors by comparing the data, plots P1 and P2 were equipped with, respectively, a commercial capacitance-based sensor (Drill and Drop manufactured by Sentek Technologies, "SAND" factory default setting) and a tensiometer (Watermark manufactured by Irrometer). Measurement depths and positions with respect to the drip line were the same as with the Pilowtech sensors. Time series produced by the commercial capacitance sensor were post-calibrated with respect to the average of the series produced by the Pilowtech (coefficient of 0.621) in order to adapt the measurement of the commercial probe to the local soil type and to allow comparison of the data. Installation of the Pilowtech in the field required the use of a graduated auger and a fence post to attach the acquisition module. The capacitance probe was inserted vertically into the soil after moistening the substrate to guarantee a good contact between the soil and the probe.

3. Results

3.1. Design of the Pilowtech, a decision-support tool for irrigation management

3.1.1. Hardware

The hardware design of the soil moisture sensor is easy and quick to make (about 30min.). The electrical assembly was simplified in order to be as reproducible as possible (Fig. 2). The sensor was configured with two analog inputs for two capacitance probes, thus allowing soil moisture to be measured at two depths at each location. Access to the plug for

Table 2
Soil samples properties.

Sample	Clay%	Silt%	Sand%	OM%	EC(mS/cm)	$WP_{4.2}$%	$FC_{2.5}$%	Bulk density(g/cm^3)
S1	4.25	3.55	92.20	0.52	0.18	6.97	10.37	1.56
S2	7.24	1.86	90.90	0.84	0.13	7.03	10.87	1.66
S3	3.91	2.58	93.51	0.76	0.12	5.88	9.52	1.68
P1	8.03	1.85	90.11	0.49	0.09	7.00	10.71	1.6
P2	4.84	1.75	93.41	0.68	0.11	5.83	9.41	1.57
P3	7.89	1.75	90.36	0.68	0.11	7.05	10.65	1.62

OM=Organic material; EC=Electrical conductivity; WP=Wilting point; FC=Field capacity.

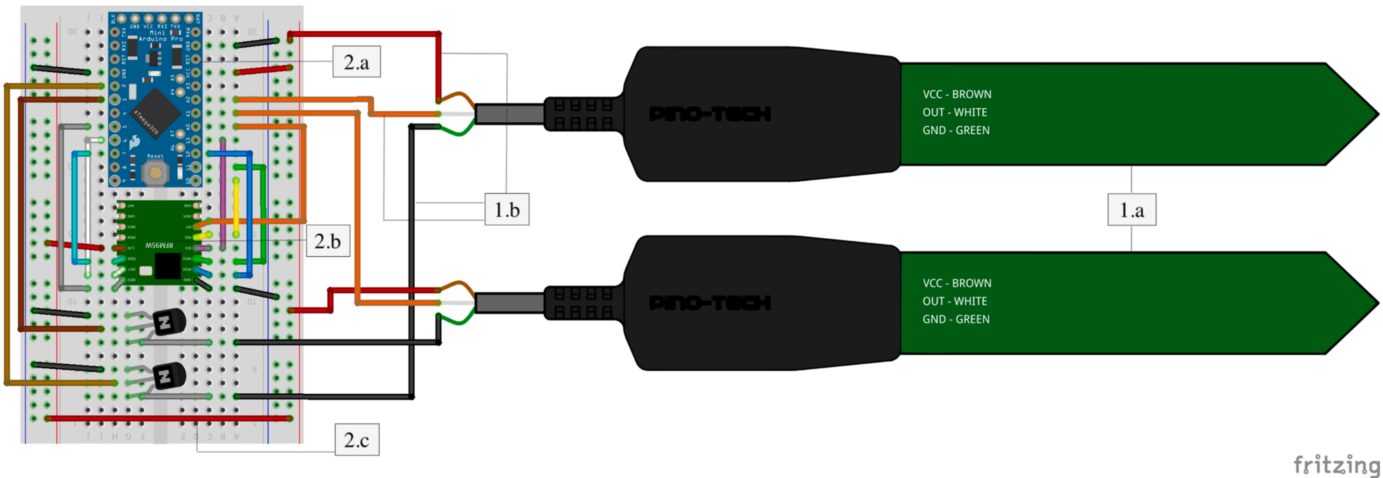

Fig. 2. Electrical circuit of the Pilowtech sensor. The numbers refer to Table 4.

on-site reading was by means of a screw cap at the above-ground extremity of the PVC tube.

3.1.2. Results of calibration

The results of the laboratory calibration are presented in Fig. 3. The digital values returned by the sensor in air and in water were $\epsilon_a = 437$ and $\epsilon_w = 202$, respectively. The sensor displayed a digital value of $\epsilon_s = 434$ in the presence of dry soil ($\theta_v = 0\%$). The curve decreased, reflecting the inverse relationship between moisture content and output voltage: the wetter the soil, the lower the output voltage, and therefore the lower the digital value returned. The distribution of the data shows a linear trend at low soil moisture content and then an increase in the slope above a threshold (around 6% moisture content) suggesting the existence of a vertical asymptote. This type of behavior can be described by an exponential relationship between ϵ and θ. From these results, we constructed the following empirical equation:

$$\theta_v = -\frac{1}{k}\ln\left(\frac{\epsilon_s - \epsilon_w}{\epsilon_a - \epsilon_w}\right) \quad (2)$$

where k is a parameter depending on soil properties, ϵ_s, ϵ_w and ϵ_a are respectively, the sensor output variable, the sensor constant value in water and the sensor constant value in the air. Therefore, the expression of volumetric soil moisture can be modeled as a function of the output voltage variable and three parameters depending on the soil type (k) and the probe used (ϵ_w, ϵ_a). This model appears well fitted ($R^2 = 0.972$) with respect to the data obtained from the laboratory calibration (Fig. 3).

The use of Eq. (2) assumes the following:

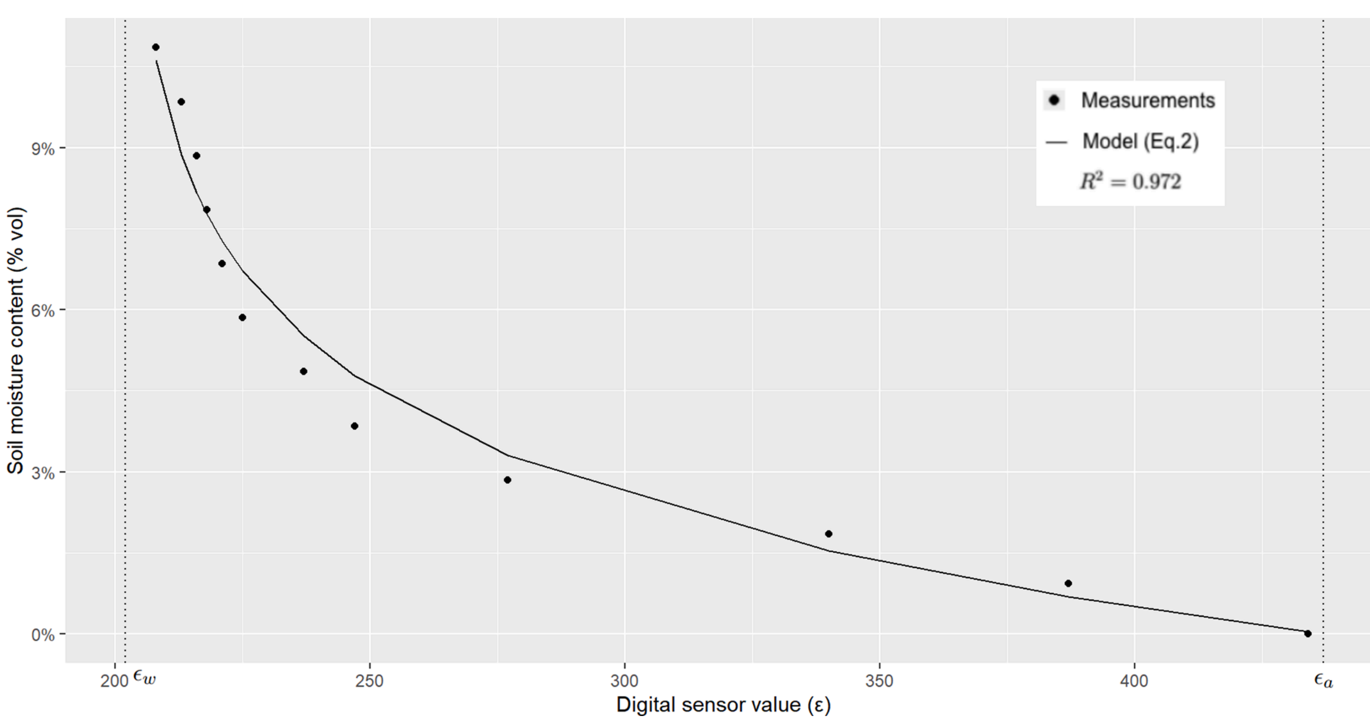

Fig. 3. Laboratory calibration of the soil moisture sensor.

$$\begin{cases} \epsilon_s \in \left]\epsilon_w;\epsilon_a\right] \\ \lim_{\epsilon_s \to \epsilon_w} \theta_v(\epsilon_s) = +\infty \\ \epsilon_s = \epsilon_a \Leftrightarrow \theta_v = 0 \\ \theta_{v\sim} = -\frac{1}{k} \cdot \left(\frac{\epsilon_s - \epsilon_w}{\epsilon_a - \epsilon_w}\right) \text{ when } \theta_v \to 0 \end{cases} \quad (3)$$

The results of the field calibration performed on the soils of the pilot plots are shown in Fig. 4. For each of the three soil samples (P1, P2, P3), the calibration is made using three different sensors (A, B, C). The results were used to parametrize Eq. (2), and the corresponding curves (models) were compared with the experimental data. The soil parameter k was determined by searching for an optimal match between the gravimetric and simulated soil moisture and minimisation of the error. Table 3 summarizes the parameters obtained. The results showed that the model based on Eq. (2) satisfactorily fitted the data obtained using the gravimetric method for all three soils ($0.875 \leq R^2 \leq 0.983$). The parameters related to the capacitance probe ranged between 182 and 198 for ϵ_w and between 430 and 479 for ϵ_a. The soil parameters obtained with the same soil sample varied little with respect to their mean ($3\% \leq c_v \leq 4\%$). However, parameter k varied more between the different soil samples ($6\% \leq c_v \leq 10\%$), parameter k is thus more sensitive to soil characteristics.

3.1.3. Software and data reading

Each farmer connected to the WSN has access to a personal space on the online platform. The data produced by the sensors are gathered for each farm and can be displayed according to the desired location, date and depth.

The calibration results allow the raw data to be displayed in the form of volumetric soil moisture (Fig. 5). Time series are available for consultation (historical and real time) and can be downloaded in different formats. In the field, the data can be accessed manually using the onsite reader. When visiting the plots, by unscrewing the top of the protective PVC tube at the desired location and depth, the farmer can simply plug in (Fig. 6a). After several trials, the farmers indicated the most practical visualization is the one that displays the filling percentage of the total available soil moisture (FP $=\frac{\theta_s-\theta_{wp}}{\theta_{fc}-\theta_{wp}}$). This percentage is visualized by means of a progress bar (Fig. 6b).

3.2. On field data evaluation: comparison with commercial water sensors

The data series produced by the Pilowtech sensors were compared with series produced by commercial sensors at two locations.

3.2.1. Ability for monitoring relative soil water status

The data obtained for plot P2 were compared with the tension measurement produced by a commercial tensiometer probe (Watermark) at the same location and depths (30 and 60 cm) as the Pilowtech (Fig. 7). Monitoring continued from March 8 to June 13, 2022, i.e. shortly after planting until the potatoes were harvested. The tensiometers were installed on March 25, before the start of the irrigation season. Irrigation was regular (frequency of around 3 days) during the development stage (April). Irrigation events were less frequent from the midseason until harvest (from May to June). The time step for data generation is 4 h for the tensiometer and around 5 min for the Pilowtech. Irrigation events are clearly identifiable from the peak moisture contents measured by the Pilowtech, and from the drops in tension measured by the tensiometer. At a depth of 30 cm, tension varied between 0 and 50 kPa. The volumetric soil moisture measured globally varied between the permanent wilting point ($\theta_{wp} = 5.83\%$ at $pF = 4.2$) and field capacity ($\theta_{fc} = 9.41\%$ at $pF = 2.5$). At a depth of 60 cm, the range of soil moisture was slightly higher (between 8% and 13%) and the range of tension was lower (between 2 and 15 kPa). At both depths, the data produced by the commercial tensiometer and the Pilowtech sensor were highly correlated. In the shallow soil layer, the probes are more sensitive to water inputs. Their variations make it possible to monitor the entire irrigation schedule, and to distinguish between the hydration and drying phases of the soil. Close to the maximum rooting depth, the response of both probes was less sensitive to drip irrigation inputs. Minor non-percolating irrigation events were less or not detected. However, analysis of moisture peaks showed that both probes reacted to irrigation events on the same dates. The sensor thus has the ability to monitor relative changes in soil moisture.

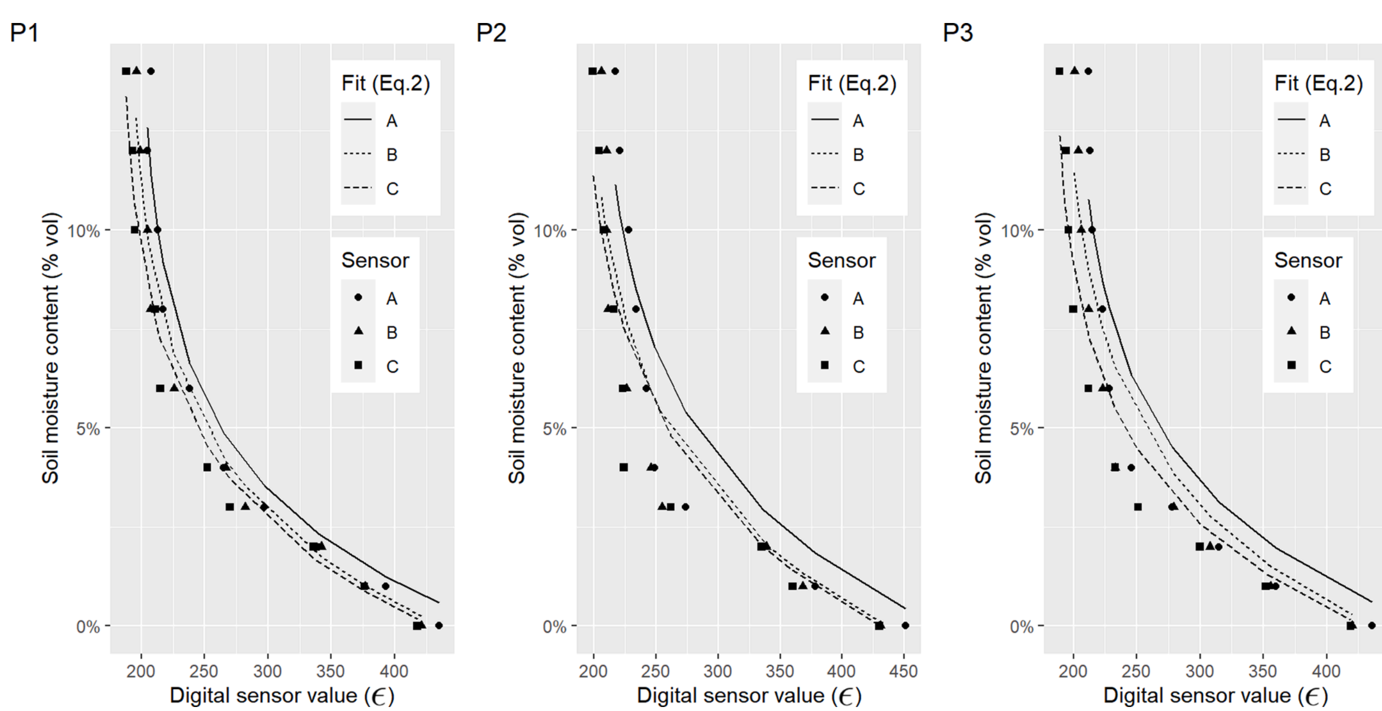

Fig. 4. Field calibration of the soil moisture sensor using 3 different soil samples (P1, P2, P3) and sensors (A, B, C).

Table 3
Parameters for 3 different soils (P1, P2, P3) and 3 sensors (A, B, C).

	P1-A	P1-B	P1-C	P2-A	P2-B	P2-C	P3-A	P3-B	P3-C
ϵ_w	198	189	182	198	189	182	198	189	182
ϵ_a	479	438	430	479	438	430	479	438	430
k	0.293	0.278	0.278	0.242	0.248	0.236	0.279	0.265	0.288
R^2	0.958	0.979	0.983	0.894	0.875	0.879	0.913	0.928	0.958

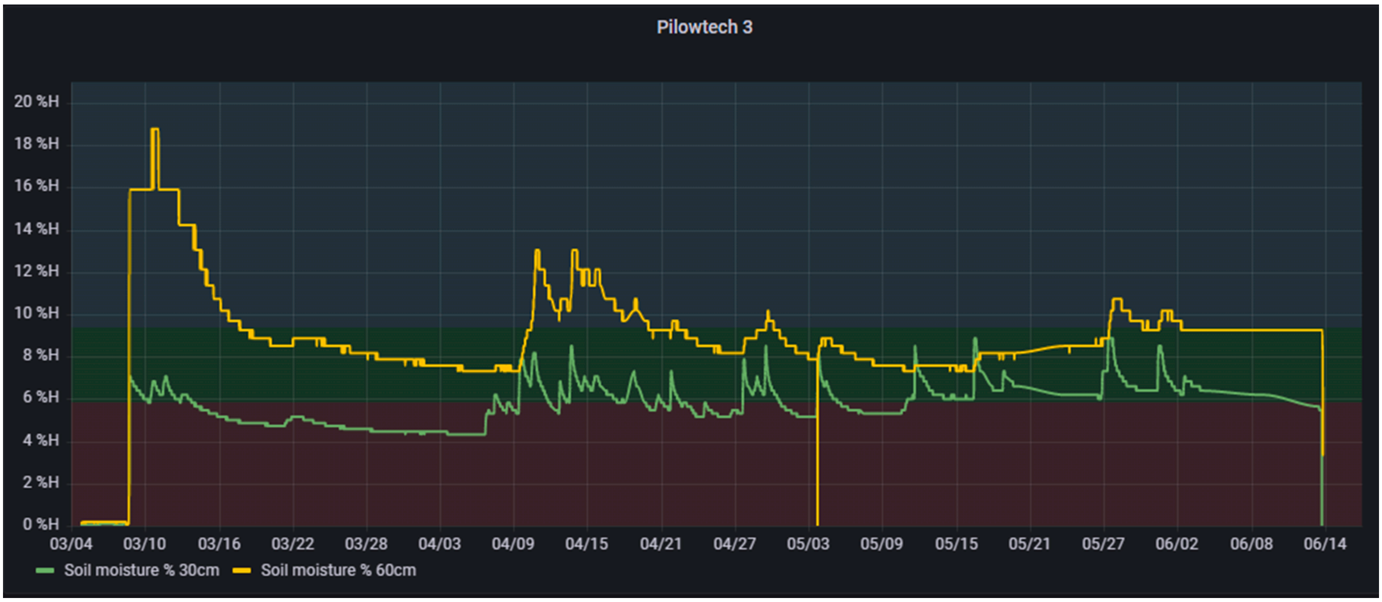

Fig. 5. Soil moisture time series as displayed on the online reading platform.

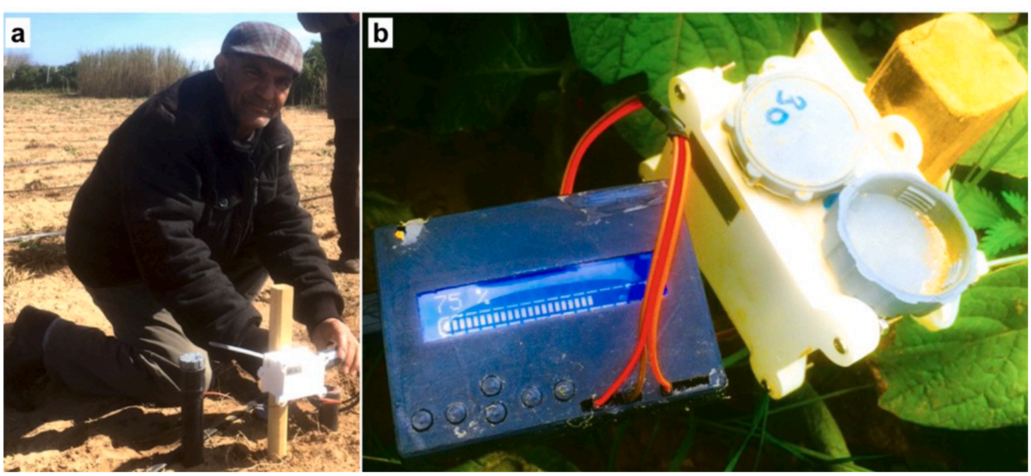

Fig. 6. Reading the soil moisture status in the field using the Pilowtech: (a) farmer plugging into the sensor and (b) display showing available water content (%).

3.2.2. *Ability for absolute soil moisture monitoring*

In plot P1, the measurements made with a commercial capacitance sensor and the Pilowtech (30 and 60 cm) from April 4 to May 3 were compared (Fig. 8). The data generation time step of the commercial sensor is 1 h, and around 5 min for the Pilowtech. Comparison of the soil moisture content characteristics measured in the plot "P1" ($\theta_{wp} = 7.00\%$ at $pF = 4.2$ and $\theta_{fc} = 10.71\%$ at $pF = 2.5$) showed that the range of moisture content measured by the commercial probe and by Pilowtech was globally bounded by the permanent wilting point and field capacity. We also compared the potential of detection of irrigation peaks, corresponding to local maximum soil water moisture content. Results revealed an excellent temporal match, confirming that irrigation events were accurately detected by both sensors. The ability of the Pilowtech to measure the intensity of irrigation events was further analyzed by comparing the magnitude of changes in soil moisture recorded by both probes during the first month of monitoring (Fig. 9).

The magnitude of an event was calculated as the difference between the maximum peak moisture measured following an irrigation event and the minimum moisture value preceding the same irrigation event. The results showed a good correlation between the magnitudes recorded by the two probes for low and medium intensity events ($\Delta < 4\%$). On the other hand, the gap between measurements by the two probes was larger in the case of more intense, higher magnitude events ($\Delta > 4\%$). Under these conditions, the Pilowtech sensor gave higher amplitudes than

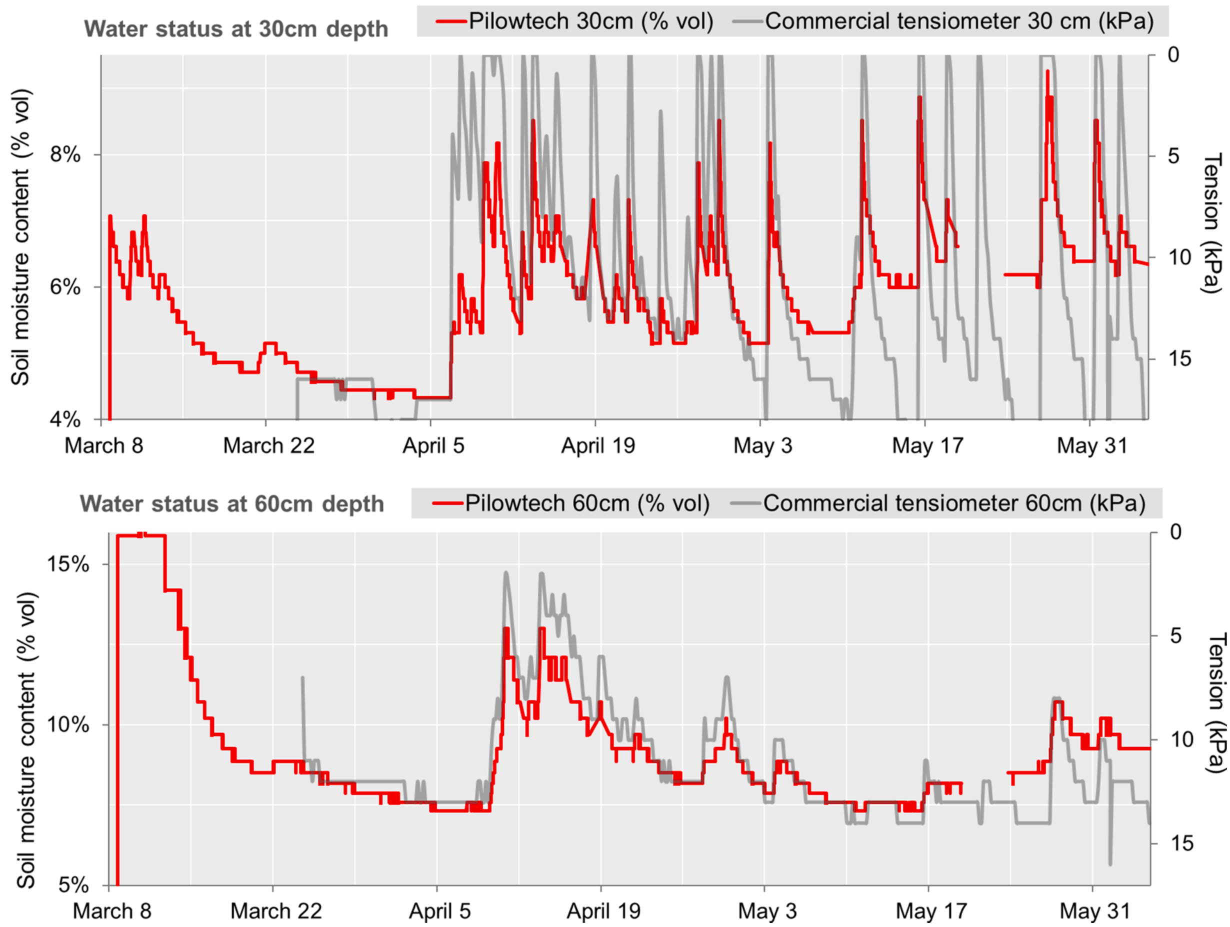

Fig. 7. Monitoring of water status in plot "P2": comparison between the Pilowtech (red curves) and a commercial tensiometer sensor (gray curves). The Pilowtech data gap from May 20 to May 23 was due to a power failure, independently from our system.

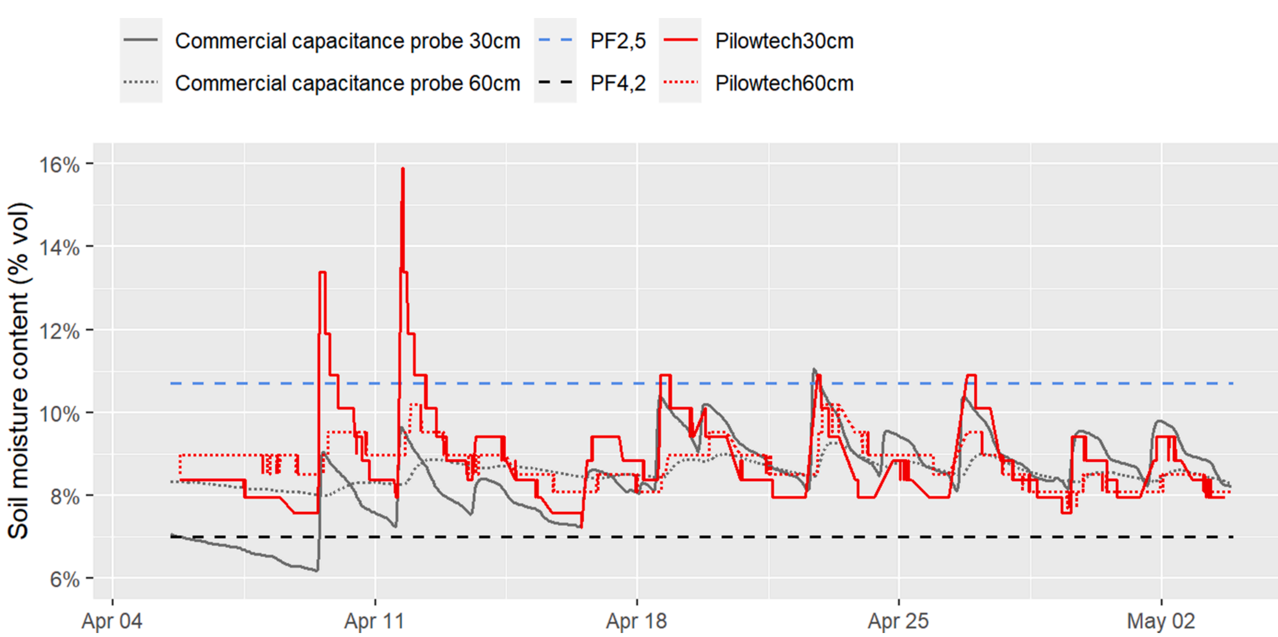

Fig. 8. Monitoring soil moisture content in plot "P1": comparison of the Pilowtech (red curves) and a commercial capacitance sensor (gray curves).

those measured by the commercial probe. This difference could be explained by the different sampling intervals used in sandy soils with high hydraulic conductivity. These behavioral variations could also be the result of drift trends the experimental data did not allow us to characterise.

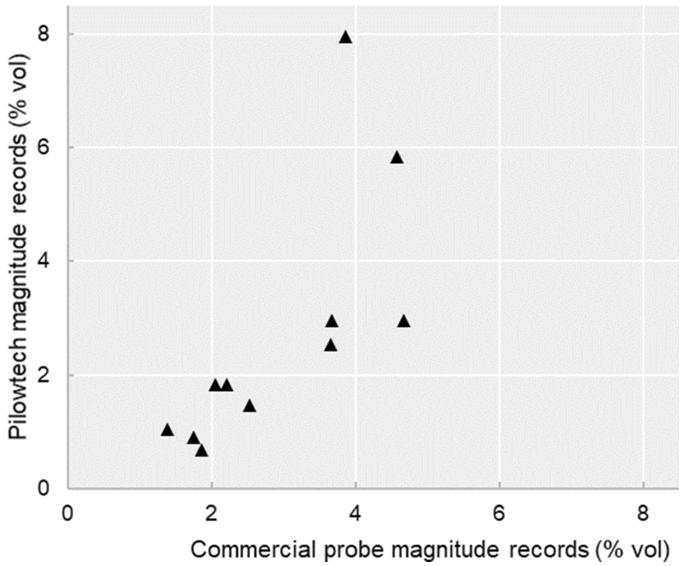

Fig. 9. Monitoring soil moisture content in plot "P1": comparison of the magnitude of changes in soil moisture recorded by the Pilowtech and a commercial capacitance sensor.

3.3. *Provisioning and maintenance*

3.3.1. *A low tech sensor with reasonable maintenance requirements*

The system was designed to be low power and to enable several months' autonomy with a 3.7 V battery. The main maintenance tasks during the season were: (i) battery management; (ii) network troubleshooting; (iii) hardware maintenance. At the end of the 102-day monitoring period, one sensor out of the eight installed needed its battery recharging. The first assumption made in the event of a gap in the data time series is that the battery is empty. After checking the voltage, the second hypothesis is a network failure. A few occasional network interruptions required maintenance tasks over the course of the season, the origins of which were identified as follows: power supply failure at the gateway or an interruption in Wi-Fi coverage at the gateway location. Finally, once the network and the power supply have been checked, a gap or an anomaly in the data time series may be due to hardware failure. The connectors in the acquisition module and at the junction with the probes should then be checked. Direct reading in the field may be necessary to check the quality of the data provided by the probe. Out of the 16 probes installed (2 per sensor), 25% of the probes showed occasional anomalies that required a technical intervention. In these situations, the probes produced unstable and inconsistent data in the data series that were easy to identify. As these events occurred following irrigation events, we assume they were due to faulty seals resulting in leakage into the probe's electronic circuits. In this case, technical maintenance consists in removing the damaged probe, and drying or replacing it, and making sure it is watertight. The resulting anomalies in soil moisture data time series can also be easily cleaned.

3.4. *A low-cost sensor with adjustable costs*

Table 4 summarizes the costs required to design a low tech soil moisture sensor. The cost of production is adjustable depending on requirements. The components needed for the sensor itself cost less than 10€ with an onsite reading system only, less than 15€ for a wireless sensor, and a total of slightly more than 20€ for the sensor with a double data reading mode. For the wireless solution, setting up a LoRa network requires a gateway (costing between 50€ and 300€) and an Internet connection. However, this investment is sufficient to network an unlimited number of sensors, which allows the costs to be amortized or shared between users. The low cost hardware and free software of the Pilowtech thus make the sensor highly affordable.

Table 4
Low-tech soil moisture sensor cost table.

S.N	Component	Cost (€)
1.	Capacitance probes	
a.	Capacitance soil moisture sensor v1.2 × 2	1.56
b.	Dupont wires 30 cm x5	0.5
	Subtotal capacitance probes	2.06
3.	Onsite data reader	
a.	Arduino Uno R3	3.36
b.	Shield Arduino LCD	3.91
	Subtotal onsite reading double depth sensor	9.33
2.	Acquisition module	
a.	Arduino pro mini 3.3V	3.35
b.	LoRa microchip SX1276	4.10
c.	Small connectors	2.00
d.	Li-ion 18,650 rechargeable battery	1.83
e.	18,650 battery slot	0.3
	Subtotal wireless double depth sensor	13.64
	Total online & onsite reading sensor	20.91

4. Discussion

Has irrigation monitoring using soil moisture probes become accessible to any water user? We developed a soil moisture sensor based on the specifications and feedback provided by the water users of an irrigation scheme. The sensor we developed is (i) low tech, meaning easy to make, maintain and reproduce; (ii) low cost, so small farming systems can afford it; (iii) low power, and consequently relatively self-sufficient and sustainable over time;

(iv) meeting farmers' expectations for monitoring water status in the root zone. The data can be accessed in two ways: remotely via an online interface, or in the field through direct reading. Calibration is feasible both in the laboratory and in the field. The sensor rating curve (Eq. (2)) is given by only one parameter, k, characteristic of the soil. This rating equation provides a reliable prediction of volumetric soil moisture once it has been parameterized. The sensor allows soil moisture to be monitored at two depths and can be used as a decision support tool for irrigation scheduling. Comparison with commercial probes highlighted the good performance of the Pilowtech sensor for irrigation scheduling and for monitoring relative soil moisture.

The low recording frequency of the commercial tensiometer, capillary hysteresis processes and the low water holding capacities of the soils prevented accurate plotting of sandy soil retention curves [28]. To go further, a laboratory experiment conditions would allow comparison of the Pilowtech sensor results with the predictions of the Van Genuchten function for a sandy soil [29]. The measurement of absolute soil moisture was satisfactory compared with that of the commercial capacitance probe, but the measurement may be subject to slight deviation over time. A metrological study, specific to the monitoring of the deviation by multiplying the controls and measuring battery discharge rates, should enable conclusions to be drawn concerning these effects. At the level of the farm or of the irrigation scheme, the number of sensors could be multiplied to create a wireless sensor network based on the LoRaWAN protocol. The data produced in real-time can be used by different types of stakeholders: (i) by farmers as a decision-support tool at the field and farm levels; (ii) by irrigation scheme managers and agricultural advisors to assess water requirements and advise water users; (iii) by researchers, for whom the production of these data will help assess performance gaps, compare practices and feed model scenarios.

Recent advances in on-board electronics and IoT therefore appear promising for the agricultural sector and particularly for water management, to the extent that they led to the development of both economically and technically accessible measurement tools. The plasticity of these systems is particularly interesting because it makes the tool adaptable to the agrarian context: for instance, we were able to adapt the data reading system to the users. Moreover, the open source nature of the system transforms the traditionally "black box" sensor into a tool that can be fully programmed by the user. Thus the user can calibrate the Pilowtech according to the characteristics of his/her field, which makes it better suited and therefore more reliable than a default pre-calibrated probe. On the other hand, it is important to stress that these advantages are not necessarily considered as such by every farmer. Indeed, the "do it yourself" approach may be seen as a limitation as it requires time to get used to it, more regular maintenance, and a certain level of agronomic expertise. These limitations can be overcome by supporting users, notably through training or by providing technical support. The scale of the irrigation scheme, and user collectives such as water users associations, appear to be a suitable environment to host a Fab lab, making it possible to pool maintenance interventions and the expenses involved in running wireless sensor networks. The Fab Lab also appears as a valuable environment for user training, notably regarding the calibration process, which although not requiring any special equipment, may nevertheless demand some ability. Another alternative could be for further studies to produce tables associating parameter values with major soil types.

Currently, the use of these technologies is facilitated by the growing importance of the community involved in this domain, the multiplication of suppliers worldwide, and the trend towards simplification of components and reduction of their costs. However, component costs still depend on the market, and are consequently sensitive to fluctuations (the Covid-19 pandemic, for example, led to a worldwide shortage of electronic chips). Hence, the equipment used in the present study will inevitably evolve with technical advances and market changes, which is not a problem as long as the equipment remains highly affordable and available from local suppliers. In any case, the Pilowtech sensor was designed as an evolving tool, necessarily subject to change through redesign and "bricolage", as signs of its re-appropriation by users [30]. Future studies should focus on the multi-criteria (agronomic, environmental, hydraulic, socioeconomic) impacts of the adoption of such tools for irrigated agriculture, including paying attention to potential side effects [31,32]. Some work remains to be done before massive use of this type of technology is achieved, and particular attention will have to be paid to the mechanisms of adoption and the means to promote the dissemination of the innovation among farmers and water users. After all, there is nothing to prevent the adjustment of this sensor to a variety of contexts, for irrigation management of diverse cropping systems or for environmental monitoring, at the same time bearing in mind that "not everything that can be counted actually counts".

5. Conclusion

The use of new technologies for agriculture does not necessarily need to be expensive, complex and energy intensive. We designed a low-cost, open source, low-tech and low-energy soil moisture sensor for monitoring crop irrigation. The calibration method implemented is simple, based on only one parameter, and allows real time monitoring of the fulfillment of the water requirements of an irrigated crop, in the present case, potato. The irrigation schedule can therefore be adjusted accordingly. Comparison of our low-cost sensor with commercial probes in field conditions over a whole irrigation season underlined the good performance of the Pilowtech sensor. The sensor can be used as a decision-support tool for real-time water management. At the scale of an irrigation scheme, the skills and costs of the equipment required to build a wireless sensor network could be shared between users. Soil moisture probes are known as a driver to achieve water savings, and this study provides a way to make them accessible, although they require more regular maintenance than existing commercial ready-to-use solutions. We believe that this study contributes to the democratization of the use of new technologies in agriculture and provides keys to facilitating their adoption, in both the North and the global South. Future work should focus on assessing the impacts of the adoption of such innovation, and its adaptation to different contexts.

Research data

All the software required for the design of the low-cost soil moisture sensor [33].

(1) Upload "Pilowtech sx1276 arduino" file on Arduino IDE, fill in your sensor information and upload it on your Arduino Pro-Mini microcontroller.
(2) Upload "Onsite reader arduino" file on the Arduino Uno and fill in your calibration parameters for onsite data reading.
(3) Upload the "3D package" file to a 3D printer to get your sensor packaging.
(4) Upload the "Nodered dataflow" file to Node-RED and adapt it to your data flow to get your sensor network ready.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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