

EVALUATION OF NOVEL APPLICATIONS OF LOW COST CAPACITIVE SENSORS FOR IRRIGATION MANAGEMENT

ÉVALUATION DE NOUVELLES APPLICATIONS DE CAPTEURS CAPACITIFS À FAIBLE COÛT POUR LA GESTION DE L'IRRIGATION

G. Ingersoll¹, and C. Leauthaud ^{2,3}

ABSTRACT

This study investigates the factors which influence the readings of a low cost soil moisture sensor (SN0308, DF robot) as part of an effort to develop a soil moisture protective coating methods sensing system which is low cost and easily deployable for use in irrigation scheduling. Specifically, this study investigates the influence of temperature, bulk density and three on sensor reading. It was found that there is an intrinsic difference between sensors. While the less robust methods of protection did not have an effect on sensor readings, the readings of sensors treated with an epoxy coating method and a 3D printed cap, the most robust protection method tested, were much lower than all other coatings. Lastly, it was found that sensor readings have a negative relationship with bulk density. These elements must be quantified and accounted for in the practical deployment of these sensors.

This study will continue to investigate the following several factors. It will investigate the relative influence of these factors, and the effect they have in combination. It will investigate the long term robustness of these sensors, and the various protective methods employed. It will investigate the response of these sensors to soil moisture. It will investigate the accuracy of various calibration methods and models. Lastly, it will investigate methods of utilizing the uncalibrated values of the sensor for irrigation scheduling (e.g., identifying wetting fronts).

Keywords: Irrigation management; Soil moisture sensor; Protective coating methods; Irrigation scheduling.

RÉSUMÉ

Cette étude examine les facteurs qui influencent les mesures d'un capteur d'humidité du sol à faible coût (SN0308, DFRobot), dans le cadre du développement d'un système de mesure de l'humidité du sol peu coûteux et facile à déployer pour la programmation de l'irrigation. Plus précisément, elle étudie l'influence de la température, de la masse volumique apparente et de trois méthodes de revêtement protecteur sur les mesures du capteur. Une différence intrinsèque entre les capteurs a été mise en évidence. Si les méthodes de protection les moins robustes n'ont pas eu d'effet sur les mesures, celles des capteurs traités par un revêtement époxy et munis d'un capuchon imprimé en 3D — la méthode de protection la plus robuste parmi celles testées — étaient nettement inférieures à celles obtenues avec tous les autres revêtements. Enfin, les mesures du capteur se sont révélées négativement corrélées à la masse volumique apparente. Ces éléments doivent être quantifiés et pris en compte lors du déploiement pratique de ces capteurs.

L'étude se poursuivra par l'examen de plusieurs facteurs. Elle évaluera leur influence relative ainsi que leurs effets combinés, la robustesse à long terme des capteurs et les différentes méthodes de protection employées. Elle étudiera également la réponse des capteurs à l'humidité du sol, la précision de diverses méthodes et de différents modèles d'étalonnage, ainsi que les moyens d'utiliser

¹ University of California, Center for Agroecology, Santa Cruz, United States

² University of California Agriculture and Natural Resources (ANR), Davis, United States

³ University of California, Santa Cruz, Environmental Studies Department, Santa Cruz, United States Corresponding author: C Leauthaud, UC Santa Cruz, Department of Environmental Studies, 1156 High Street, Santa Cruz, CA 95064, USA. e-mail: crystele.leauthaud@cirad.fr

les valeurs non étalonnées des capteurs pour programmer l'irrigation, par exemple en détectant les fronts d'humectation.

Mots clés : Gestion de l'irrigation; Capteur d'humidité du sol; Méthodes de revêtement protecteur; Programmation de l'irrigation.

INTRODUCTION

A wide range of irrigation monitoring tools including model-based control strategies, automation systems, remote sensing, and in-field sensing have been developed in the past decades. However, despite years of research and extension on irrigation, widespread adoption of such technology and science-based water management strategies has not occurred. For Irmak (2023), the primary characteristics of technology with strong adoption potential are price, durability, ease of use and interpretation, and firm scientific grounding.

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. In parallel, there is an increase of sensing tools available on the market at substantially lower costs. However, the accuracy of these low cost sensors has yet to be evaluated, and the manufacturer does not provide pre-calibrated equations. The time and labor required to carry out this calibration protocol presents a severe barrier to the deployment of capacitive sensors in agricultural irrigation management, in particular for small scale farmers in California.

This study provides a preliminary assessment of the effect of a number of variables including intrinsic sensor variability, temperature and bulk density. The study also assesses the effect of three protective coating methods intended to improve the sensors' resilience to environmental degradation. A future version of this study will assess the relative impact of these various factors and their cumulative effects. The intent of this investigation is to understand how the elements of cost, preparatory labor and complexity can be balanced to achieve the most accessible means of utilizing this low cost sensor for irrigation scheduling.

METHODS

Data collection

Four boxes of approximately the same volume were constructed from plywood. Each box was then weighed and their volumes were calculated. High organic matter garden soil was allowed to air dry for several days. An amount of this soil was then added to one box without performing any compaction. Soil was then added to another box while performing maximum compaction. The mass of soil in each box was then weighed and their bulk density was determined. A bulk density approximately half way in between these two values was determined and that mass of soil was added to a third box. At this time several samples of soil were collected in order to determine the soil's initial massic water content, which was found to be approximately 58%. The researchers hypothesize that this high value can be attributed to the soil's high organic matter content.

In-air and in-water values were taken for 55 capacitive soil moisture sensors (SN0308, DF robot). These readings were used both to assess intrinsic sensor variability and to screen for defective sensors. From this initial pool, 40 sensors were chosen to be used for data collection. Sixteen sensors were equipped with a 3D printed cap which was filled with epoxy resin and had their edges dipped in epoxy. Eight sensors had the front section of their plastic casing removed and filled with epoxy resin. Eight sensors had their edges and the gaps in between their plastic casings covered in hot glue. Eight sensors were left protected. These sensors were then wired to SN50v3 nodes (Dragino) and connected via a LoRa network to a cloud server through the Grafana service (Grafana labs).

The epoxy coating treatment required the most labor, and the additional step of creating a 3D printed cap, but was hypothesized to be the most resilient to environmental degradation. While the epoxy drenched treatment required less labor, it was still cumbersome. Lastly, the glued treatment was the least labor-intensive treatment, but was hypothesized to provide the least amount of protection. In each box (Figure 1), were placed four epoxy coated sensors, two epoxy drenched sensors, two glued sensors, two untreated sensors and two Teros 12 sensors (Meter group). Although not examined in this preliminary analysis, the Teros 12 sensors will be used as a benchmark against which to compare the accuracy and robustness of the SN0308 sensors. The location of each sensor was chosen at random.



Figure 1. Data collection setup. The picture on the right shows the sensor layout of a box.



Figure 2. Sensor protection treatments. Upper left: Unprotected sensor, Upper right: Epoxy coated sensor, Lower left: Epoxy drenched sensor, Lower right: Glued sensor

Data analysis

Data analysis was performed with R (R Core Team, 2025), using the packages dplyr (Wickham et al., 2026), lubridate (Grolemund & Wickham, 2011), readr (Wickham, Hester & Bryan 2026) and ggplot2 (Wickham, 2016). Initial in-air and in-water readings for each sensor were adjusted from their absolute value to a ratio using the following two part calibration equation:

Sensor value' = (Sensor value - minimum sensor value) / (maximum sensor value - minimum sensor value) An adjustment was also made to other sensor values. In all nodes, the readings of all sensors connected to a particular port number were all significantly lower than all other ports. This difference was determined to be caused by a particular feature of that port. Therefore the readings of all sensors connected to that port number were adjusted by the following method. The slope of the line between in-air values for a reference port and those of the deviant port was calculated and determined to be consistent across different nodes. The mean value of this slope for each node was calculated. The readings for all sensors connected to that port number were then multiplied by this mean slope value. This adjustment was performed as such in order to avoid a sensor specific adjustment that would mitigate the effect of other variables examined in this study.

RESULTS AND DISCUSSION

Initial readings of sensors before coating treatment

Both the initial in-air (Figure 3) and in-water (Figure 4) readings for these sensors fell into two distinct groupings. Seventeen of these sensors (45%) had in-air readings which were lower than the remaining 38 sensors. Three of these sensors (5%) had in-water readings that were higher than the remaining 52 sensors. Deviations in in-air and in-water readings were not found in the same sensors. Additionally, there appeared to be greater sensor to sensor variability for in-air readings than in-water readings.

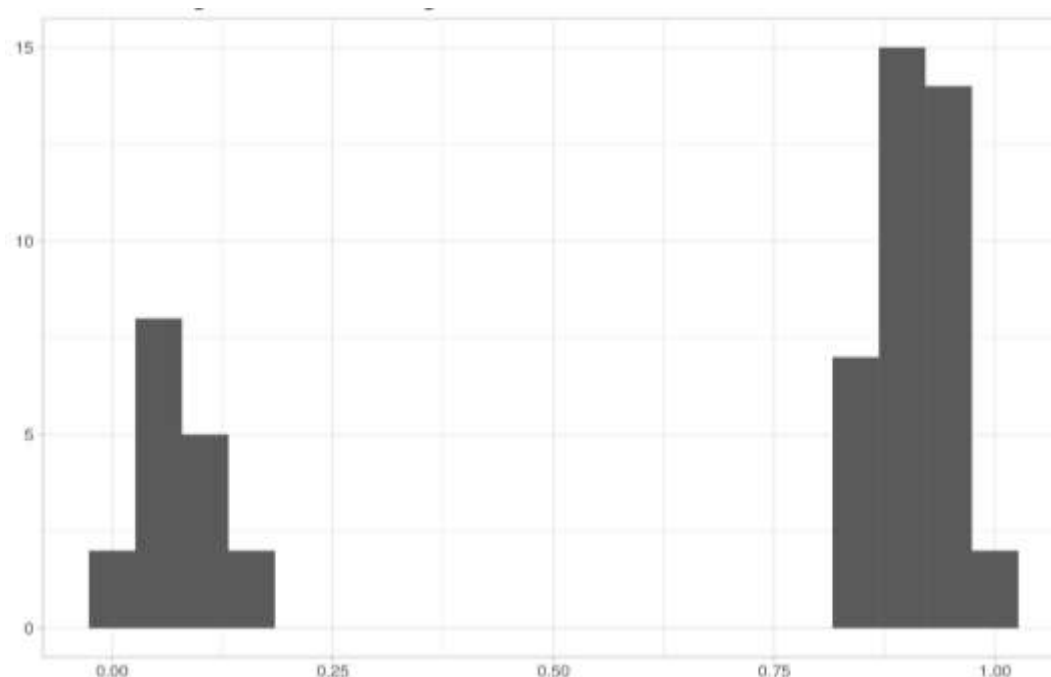


Figure 3. Distribution of sensor readings in air before coating treatment. Sensor readings have been adjusted to a ratio.

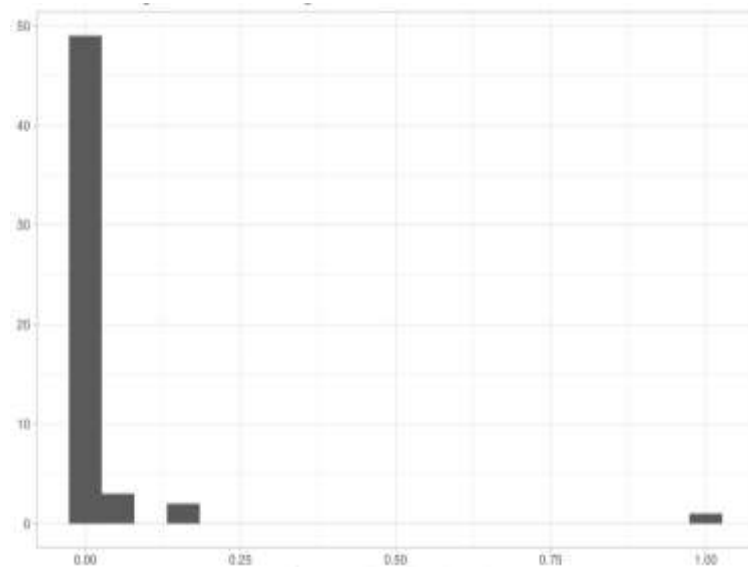


Figure 4. Distribution of sensor readings in water before coating treatment. Sensor readings have been adjusted to a ratio

These data indicate that each sensor has an intrinsic heterogeneity which influences its sensitivity. This sensor to sensor variability must be accounted for in the practical deployment of these sensors. Further, these results suggest that in order to utilize this sensor for its intended purpose of volumetric water content quantification, one should avoid using sensors with abnormal in-air or in-water readings in order to ensure accuracy.

Sensitivity of sensors to coating treatments

Epoxy coating, the most robust protection method tested, had a significant effect on in-air sensor readings (Figure 5). This coating method appears to lower the reading of the sensor by 225 units, but does not have a noticeable effect on the amplitude of sensor readings. The sensors treated with other protection methods did not deviate from the uncoated sensors. Within each treatment group, the difference between sensors which recorded maximum and minimum values was approximately 50 units, similar to the variation observed among uncoated sensors.

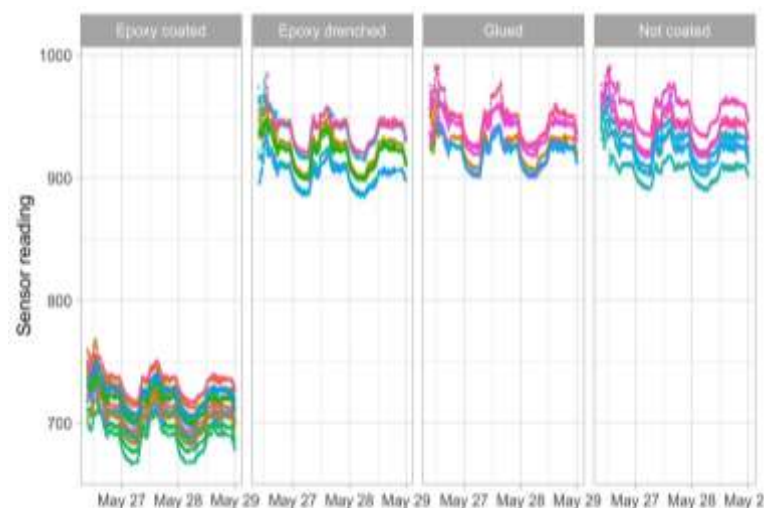


Figure 5. Sensitivity of sensors to coating treatments. Readings were taken in the air. Each color depicts an individual sensor.

The researchers hypothesize that this drastic difference between the epoxy coated treatment, and the other protection treatments is due to the presence of epoxy along the edge of the sensing device, or due to the epoxy-filled cap placed at the end of the device. However, the specific cause of this variability is yet unclear. Additionally, the consistency of variability between the unprotected sensors and all protection treatments suggest that differences in protection application have a minimal effect on sensor readings between sensors that receive the same protection treatment. Instead, the researchers hypothesize that this variability may be due to the intrinsic sensor variability observed in Figures 3 and 4.

Sensitivity of coated sensors to temperature

All coated sensors showed a clear response to ambient temperature (Figure 6). There appears to be a strong positive linear relationship between temperature and sensor reading between approximately 15 to 20 degrees celsius. Between 20 and 30 degrees celsius, some sensors display a weak positive linear relationship between temperature and sensor reading. However, as there were far fewer readings taken within this range, this relationship is difficult to determine.

These data suggest that while there may be negligible influence of temperature at 'room temperature', this variable might have to be accounted for in calibration models when deploying sensors in lower temperature environments. This sensitivity may limit the applications of these sensors in certain climate zones. The researchers will investigate this relationship at temperatures below and above the range observed in this data set. It may be that these soil moisture sensors must be used in conjunction with temperature sensors to allow for an account of this variable.

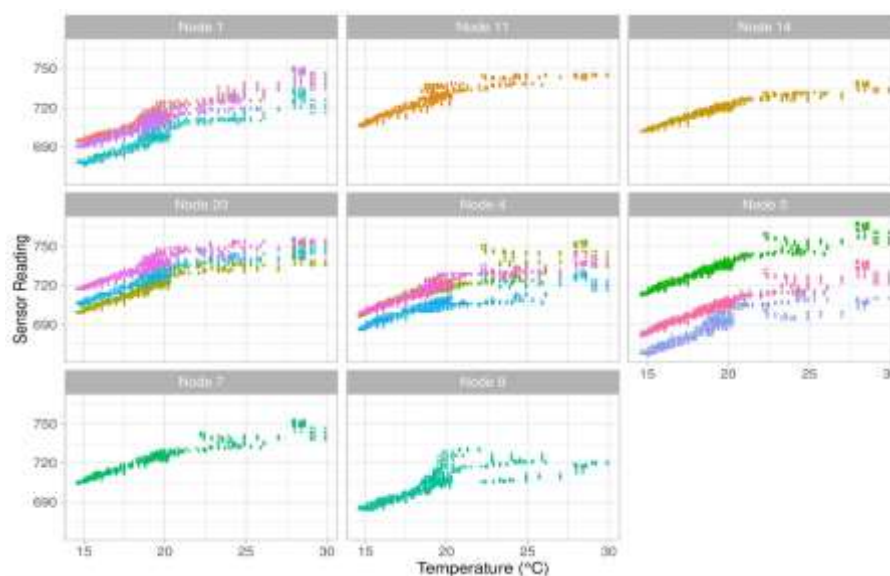


Figure 6. Sensitivity of coated sensors to temperature. Readings were taken in air over a twenty four hour period. Each color indicates a unique sensor. Data was divided into nodes that sensors were connected to for clarity of visualization.

Sensitivity of coated sensors to bulk density

Soil bulk density appears to have a large effect on the readings of coated sensors (Figure 7). Sensor values appear to decrease as a function of bulk density. A similar trend was observed in uncoated sensors as well as the other protection treatments. There also appears to be high variability for each sensor within each discrete box. However, it is unclear if this is primarily due to heterogeneity of soil bulk density within each box, differences in epoxy coating or sensor specific differences.

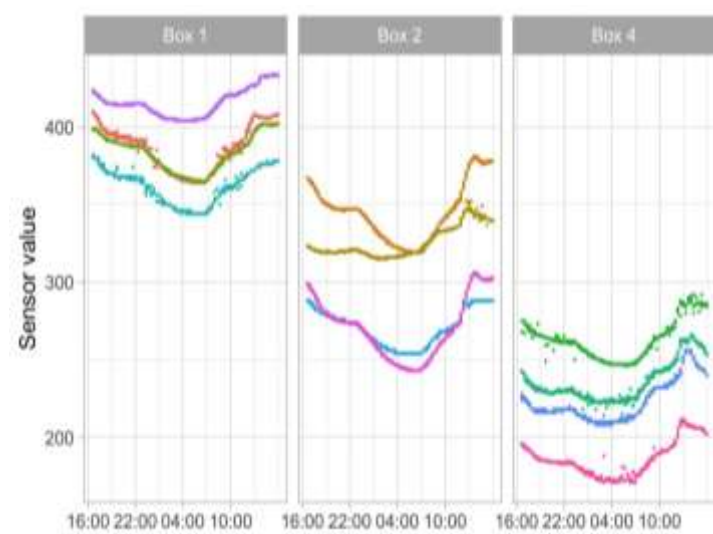


Figure 7. Sensitivity of coated sensors to bulk density. Bulk density of box 1 is equal to 0.29 g/cm³, bulk density of box 2 is equal to 0.36 g/cm³, and bulk density of box 4 is equal to 0.43 g/cm³. Each color represents a unique sensor.

The researchers hypothesize that this relationship between density and sensor value may be due to the increased presence of air pockets at lower densities. If this is the case, the effect of density may be mitigated by coating the entirety of the sensor with wet soil. The researchers will investigate sensor responses to densities between the values included in this data set, as well as densities outside of these values. It also may be the case that the magnitude of this relationship between sensor reading and density varies in different soil textures and in relation to soil organic matter content.

CONCLUSION AND FUTURE RESEARCH

This preliminary analysis suggests that the potential of this low cost sensing device for use in irrigation scheduling can only be realized once intrinsic and environmental variables are understood and taken into account. All variables investigated had an apparent influence on the reading of the sensor. There is an intrinsic difference across individual sensors, with high variability of readings in the air and more stable readings in water. Further, there is a negative relationship between bulk density and sensor reading and there is a positive relationship between air temperature and sensor reading at temperatures below twenty degrees celsius. These factors must be quantified and accounted for if these sensors are to be deployed for their intended purpose of soil moisture assessment. The next immediate step in analysis is to compare the relative impact of these variables and their combined effect. Then the response of these sensors and their various treatments to irrigation regimes will be assessed and compared to a high quality soil moisture sensor and a control value of gravimetric water content.

A future version of this study will investigate several additional factors. The response of these soil moisture sensors to soil moisture in various densities, temperatures and coating treatments will be assessed. Further, the accuracy of various methods of calibration will be assessed to determine if these sensors are capable of providing an estimation of volumetric water content that is sufficiently accurate for irrigation scheduling. Lastly, this study will investigate alternative applications of this low cost sensor that do not require the conventional calibration protocols currently recommended. We expect that this experiment will demonstrate that the calibration procedures currently recommended are not always the optimal way of using these sensors in agricultural applications.

Once these effects have been quantified, assessed, this study will assess the use of this sensor in situ conditions by placing these sensors in outdoor conditions in a mineral soil. This will allow for the further rigorous testing of sensor robustness to environmental degradation, and will allow for a

comparative assessment of the effect of soil texture on sensor readings. A follow up to this study could also investigate the effect of a range of soil textures and assess if calibration curves for different common soil textures could be developed to avoid the laborious process of the conventional calibration procedure.

Further, an analysis will be performed which compares the price, required labor, resilience and accuracy of various sensor treatments and applications. This analysis could be used to develop sensor setups adapted to different use cases. In the near future, these alternative sensor applications will be integrated into workshops with small diversified and socially disadvantaged growers in California, where their usefulness and adoption potential will be assessed.

The development and extension of irrigation management technology and methods tailored to the irrigation practices and challenges of small and diversified farms in California is important to the future of these systems, as Californian small farmers continue to contend with unstable climate conditions and strict water regulations. As the calibration procedure is currently one of the main barriers to adoption of low cost sensors, the results of this study, accompanied by the use of Do-It-Yourself IoT low-cost and open-source sensing systems, should increase adoption rate of sensing technologies and improve on-farm water management.

References

- Irmak, S. (2023). Agriculture and Agricultural Water Management: Historical Perspectives and Integration of Research and Extension/Outreach for Large-Scale Technology Adoption in Production Fields. *Journal of the ASABE*, 66(1), 167–192. <https://doi.org/10.13031/ja.15272>
- Grolemund G, Wickham H (2011). "Dates and Times Made Easy with lubridate." *Journal of Statistical Software*, 40(3), 1–25. <https://www.jstatsoft.org/v40/i03/>.
- R Core Team (2026). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.
- Wickham H, Hester J, Bryan J (2026). readr: Read Rectangular Text Data. R package version 2.2.0, <https://readr.tidyverse.org>.
- Wickham H, François R, Henry L, Müller K, Vaughan D (2026). dplyr: A Grammar of Data Manipulation. R package version 1.2.1, <https://dplyr.tidyverse.org>.