Performance assessment of soil moisture sensors

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Content

Executive summary

Introduction:

This report presents the performance assessment of three soil moisture sensors: CLIMAVIsoil, Drill and Drop, Trime-Pico32. Soil moisture sensors are critical instruments in agriculture that allow for continuous and near-accurate soil moisture measurements.

Objective:

The primary objective of this assessment is to evaluate and compare the performance of these three sensors under laboratory and field conditions. The sensors are evaluated based on key performance criteria such as accuracy, precision, ease of use, sensitivity to extreme moisture conditions.

Summary of findings:

- Accuracy: PICO > Drill & drop > CLIMAVI
- Precision: Drill & drop > PICO > CLIMAVI
- Ease of use: PICO > CLIMAVI > Drill & drop
- Moisture sensitivity: PICO is accurate under extreme moisture conditions

Key takeaways:

- PICO sensor is reliable and accurate
- Drill & drop sensor performs well but would benefit from material specific calibration
- Climavi sensor needs to be assessed to understand the sources of error

Conclusion:

This report provides a comprehensive comparison of three soil moisture sensors, presenting their strengths and weaknesses. Accuracy and precision metrics are used to assess the soil moisture sensors. The results will aid the company in making decisions about the best sensor for the agricultural weather station.

Introduction

Background:

Traditionally, soil moisture is measured through the gravimetric method which involves taking out a soil sample from the field, oven-drying the sample at 105°c for 24 hours, and calculating the mass of water as the difference in weight between the wet soil sample and the dry soil sample. However, this method does not provide continuous real-time data, it is time-consuming and laborious to carry out, it also disturbs the soil structure. Soil moisture sensors are therefore preferred as alternatives. In spite of these disadvantages, the gravimetric method is still considered the gold standard because it provides an actual measurement of the soil water content. It is used as a reference to calibrate soil moisture sensors for various applications[1].

Soil moisture sensors are instruments that allow for continuous, in-situ measurement of soil moisture content. They provide real-time data which is important for irrigation management. This technology has been widely accepted in agriculture because it provides an affordable, non-destructive and less-laborious way of determining soil moisture. It is considered an indirect method because it does not measure soil moisture. Rather, it measures other properties of the soil that changes with change in moisture content[2].

In modern agriculture, the demand for reliable soil moisture sensors has grown significantly. One of the most commonly used soil moisture sensor technologies is the electromagnetic sensors. These soil moisture sensors differ from each other in their design, measuring technology, performance, and cost. They have a wide range of measuring methods such as Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), Capacitance sensors, Resistance sensors, Time Domain Transmission (TDT)[3].

These differences between soil moisture sensors necessitates an evaluation of their performance in order to determine their suitability for use.

Purpose of the assessment:

The purpose of this assessment is to evaluate three soil moisture sensors operating on different measurement technologies: CLIMAVIsoil, Drill and Drop, Trime-Pico32. This evaluation aims to provide detailed comparison based on key performance metrics such as accuracy and precision, reproducibility, ease of use, sensitivity to extreme moisture conditions. By conducting controlled laboratory tests and field tests, the strengths and weaknesses of each sensor will be identified under these varying conditions.

Expected outcome:

- Comprehensive understanding of the performance characteristics of each sensor.
- Identification of the most suitable sensor across all criteria.

By carrying out this assessment, informed conclusions can be made on the best suited sensor for the agricultural weather station project.

Methodology

The soil moisture sensors will be assessed in the laboratory and in the field.

Laboratory Test

The performance assessment of the three soil moisture sensors (CLIMAVIsoil, Drill and Drop, Trime-Pico32) was carried out in the laboratory using fine sand (F36 sand) as the test material. The laboratory test involves creating different soil moisture contents in sand and testing the ability of the sensors to accurately measure soil moisture at each water content level.

Test material

KSE Sand F36 sand produced by Remmers Gruppe AG with an average grain size of 0.16 mm and approximately 99% SiO_2 content was selected. The selection of F36 sand was motivated by its high permeability (Ks = 2496 cm d^{-1}) and absence of organic matter, which makes it easier to create a homogeneous (and hence repeatable) testbed with uniform water content. Another benefit of F36 sand is the absence of clay and salt as these soil properties may lead to erroneous results in some electromagnetic soil moisture sensors[4].

Other materials

The following were also needed for the laboratory assessment of the soil moisture sensors:

- Container
- Weighing scale
- Tarpaulin
- Gloves
- Data logger
- Graduated water measuring container

Experimental protocol

The experiment involves estimating the actual soil moisture content using weighted difference between wet soil and dry soil. The difference in weight gives the mass of water in the soil (also known as gravimetric water content). This water content needs to be expressed on volumetric basis so that the soil moisture value is directly comparable to the output of the soil moisture sensors[5].

Steps include:

PART A – Reference Soil Moisture Measurement

- Weigh the clean dry container and record the mass, w_0.
- Determine the volume of the container by filling it with water up to a predetermined height. The mass of water multiplied by its density gives the volume of the container.
- Determine the total amount of water needed to bring soil to saturation. Sand can hold up to 35% volumetric water content at saturation.

- Determine the mass of water to be added to the container volume in order to estimate different volumetric water contents. For instance:

$$10\%\ volumetric\ water\ content\ = 10\%\ \times container\ volume$$

- Pour a known mass of dry soil into a wide bowl and add the pre-determined mass of water. Mix the sand with water until completely homogeneous.
- Pack the wet soil into the container in layers of 1cm until the container is filled.
- Weigh the container + wet soil and record the mass, w_1.
- Give the wet soil 30 minutes to 1 hour to settle from disturbances caused by packing.

Weigh dry sand

Mix sand with water

Pack sand into container

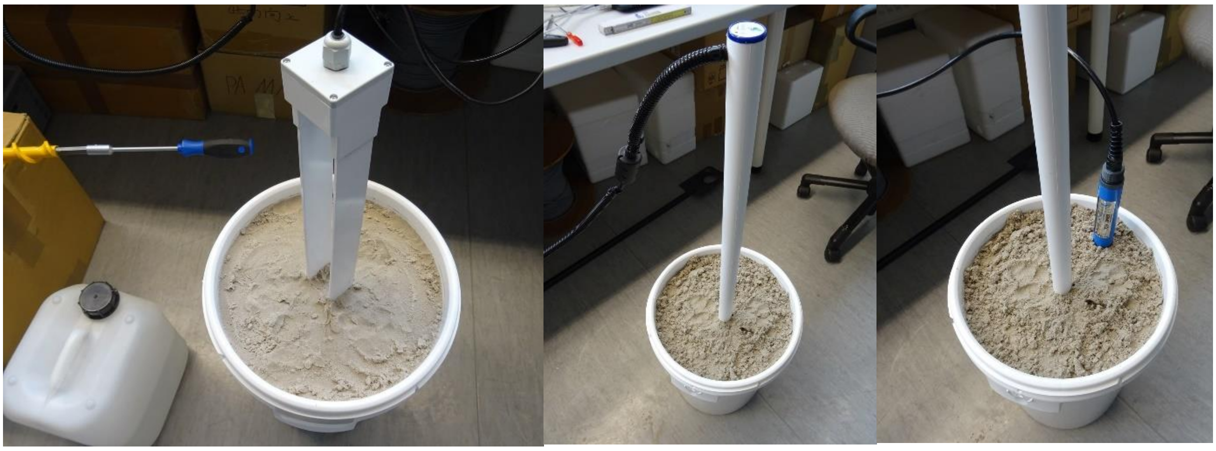
Reweigh and allow to settle

Figure 1 Reference Soil Moisture Measurement

PART B – Sensor Readings

- Soil moisture sensors should be inserted approximately 20cm away from the container wall to ensure proper coverage of the sensor measuring volume.
- Ensure all three sensors are measuring the same soil depth within the container so their results are directly comparable.
- Use the drilling tool of each sensor to insert them into the container.
- Measure soil moisture content using each sensor for 30 minutes. This allows enough time to test for accuracy and repeatability.

- Repack the soil for each sensor reading if necessary (It is necessary when the drilling tool compacts the soil in the container. This compaction changes the soil bulk density and can lead to erroneous readings).



Climavi **Drill & Drop** **Pico**

Figure 2 Soil Moisture Sensor Readings

PART C – After Measurements Calculations

- Once all readings have been taken, reweigh the wet soil in the container to account for any loss of water during the measurement process.
- Spread out the wet soil on a tarpaulin to dry for several days.
- When completely dried, pack sand into container and record the mass, w_2.
- Calculate gravimetric water content

$$\emptyset g = \frac{mass\ of\ wet\ soil - mass\ of\ dry\ soil}{mass\ of\ dry\ soil} \times 100$$

- Calculate bulk density of soil

$$\rho soil = \frac{mass\ of\ dry\ soil}{volume\ of\ soil}$$

- Calculate volumetric water content

$$\emptyset v = \emptyset g \times \frac{\rho soil}{\rho water\ (1g/cm^3)}$$

- Assess the individual sensor readings against the reference volumetric water content calculated above.

Sensor description

CLIMAVIsoil: [6]

- Manufacturer: Agvolution
- Model: NA
- Technical specifications:
    - Soil moisture probe with 3 moisture and temperature sensors
    - Three measuring depths: 0 to -15 cm, -15 to -30 cm, -30 to -45 cm.
    - Capacitive measurement technology
    - Raw electrical capacitance values available
    - Moisture range: 0 – 50% soil moisture
    - SDI-12 compatibility
    - Soil specific calibration
    - Installation kit available

Drill and Drop: [7]

- Manufacturer: Sentek
- Model: Series III Probe
- Technical specifications:
    - Soil moisture probe with a probe length of 90cm
    - 9 soil moisture and temperature sensors at 10cm interval
    - Capacitance (FDR) technology
    - Resolution of 1:10000 and precision of ±0.03% vol
    - Moisture range: 0 – 50% soil moisture
    - RS232/RS485 protocol
    - Not SDI-12 compatible
    - No soil specific calibration
    - Installation kit available

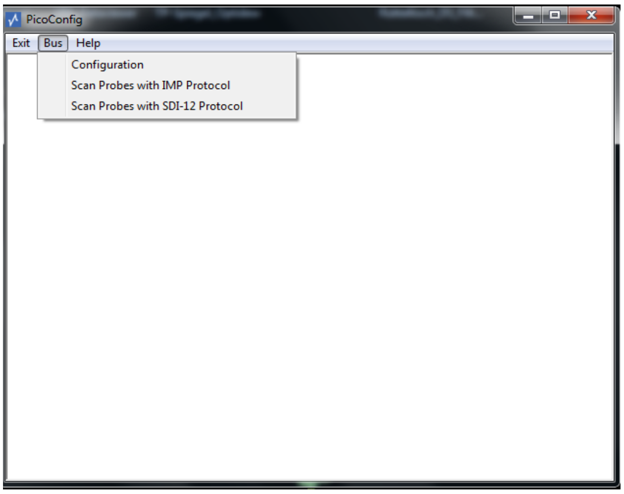
Trime-Pico32: [8]

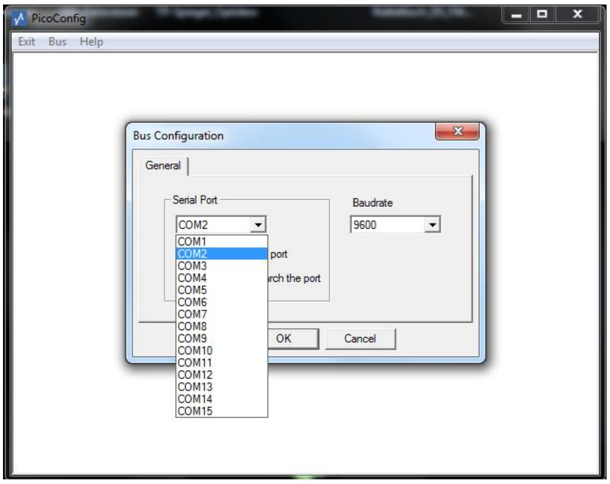
- Manufacturer: IMKO
- Model: NA
- Technical specifications:
    - Single soil moisture sensor with probe length of 11cm
    - Operation modes: bus mode, single measurement.
    - Time Domain Reflectometry (TDR) technology
    - Soil moisture accuracy: ±1%
    - Moisture range: 0 – 100% soil moisture
    - SDI-12 compatibility
    - Material specific calibration
    - Soil density correction

Software Settings

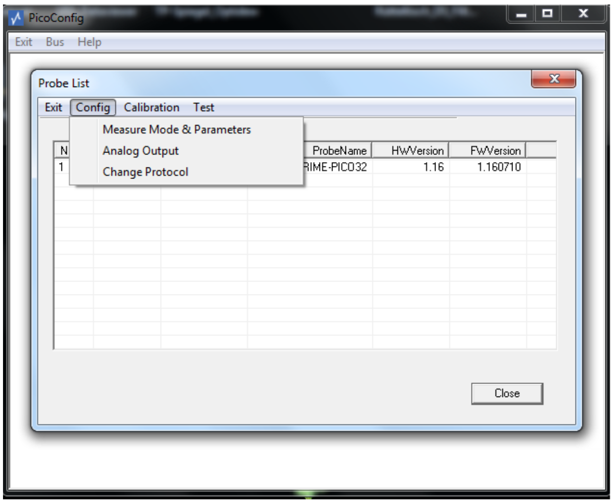
Trime Pico-32:

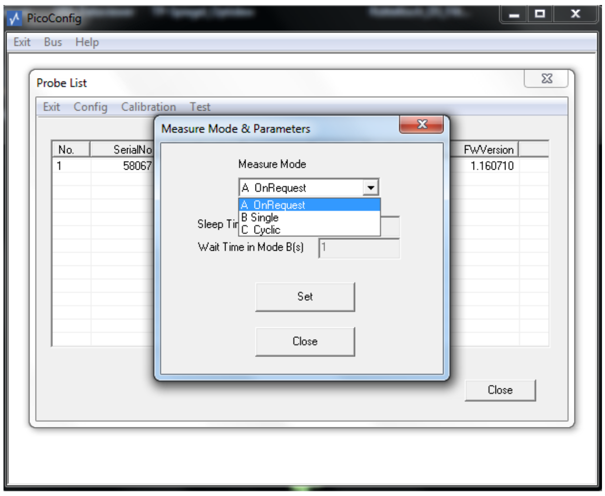
The following settings were used on the PICO-CONFIG software for Trime-Pico 32 sensor.



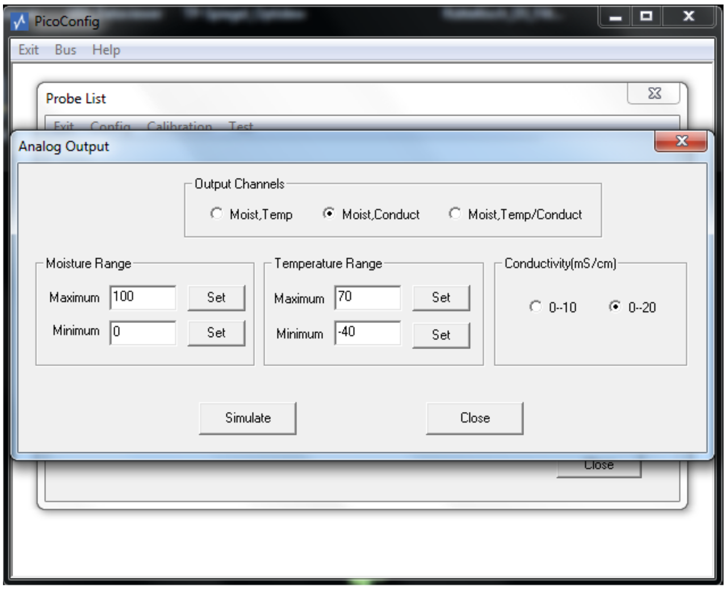


In the menu “Bus” and the window “Configuration”, the PC is configured to an available COMx port and the baud rate 9600 is selected. After configuration, the available probes can be scanned with either the IMP protocol or the SDI-12 protocol. It takes 30 seconds. Once, completed, a new window “Probe list” comes up.





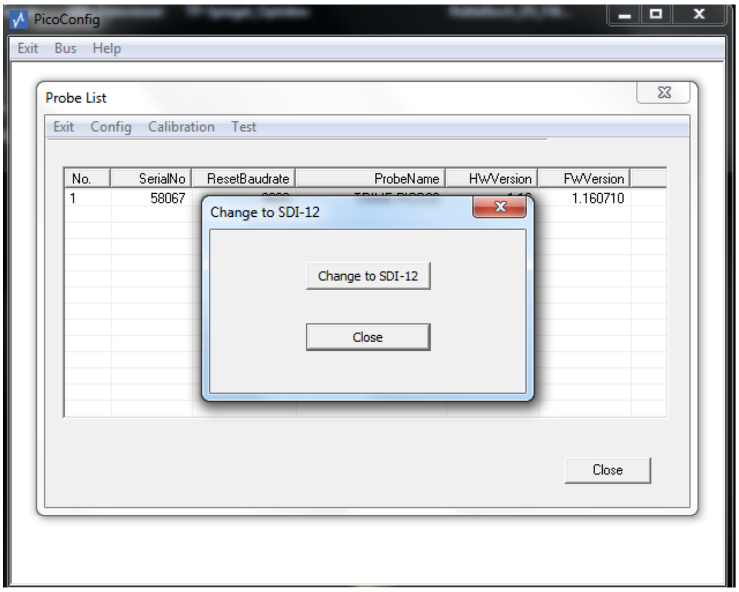
In Probe list, under “Config” and “Measure Mode & Parameters”, the sensor can be set to measure mode A, B, or C. Operation mode A (On Request) is an IMP-Bus interface and in this mode, sensor can be connected to SDI12 datalogger. In Operation mode B and C, sensor gives analogue output of 0 to 1V for soil moisture and temperature and in these modes, sensor can be connected to a conventional analogue datalogger.



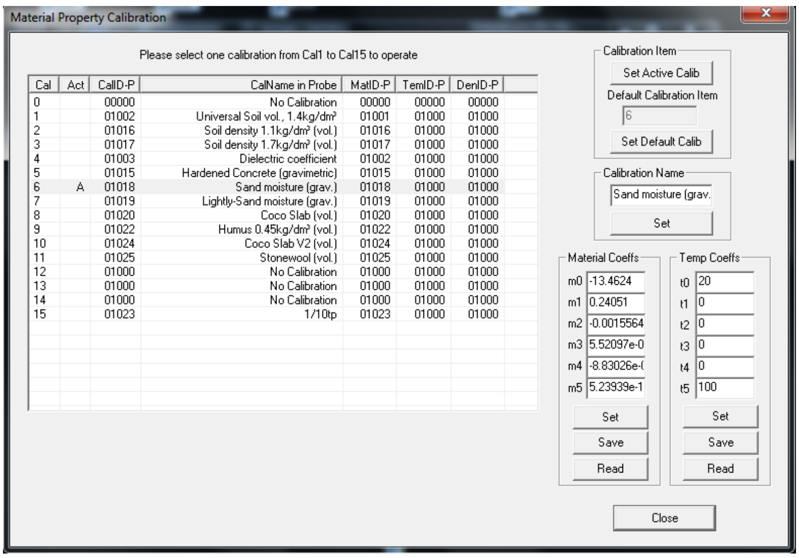
Under Probe list, in the menu “Config” and window “Analog Output”, the analog output of the sensor can be configured.

The default moisture and temperature measurement range are shown. When “Simulate” is clicked, the analog output 0-1V corresponding to the moisture and temperature range appears.

The conductivity range can be selected based on the salinity of the soil. 0 to 20mS/cm should be selected for soils with high salt content.



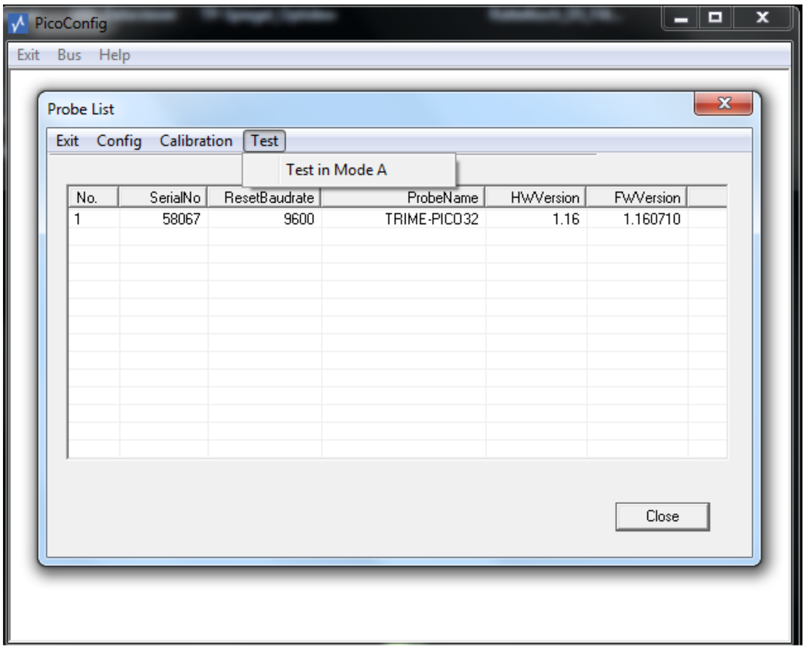
Under Probe list, in the menu “Change Protocol”, the protocol can be switched from IMP Protocol to SDI-12 and vice versa.



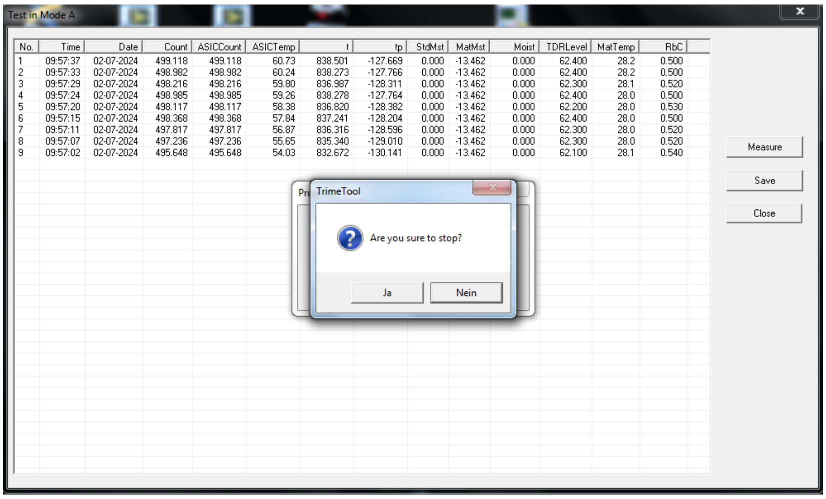
In the menu “Calibration” and the window “Material Property Calibration”, the calibration curves CAL1 to CAL15 are loaded and the preferred calibration function is selected. Non-linear calibrations are possible with polynomials up to the 5th grade using the material coefficients of each calibration function (coefficients m0 – m5).

The button “Set Active Calib” is used to select the preferred calibration function for measuring soil moisture content.

CAL1 which is the Universal Soil vol., 1.4kg/dm3 is suitable for most soil types. However, in this study, CAL6 i.e., Sand moisture (grav.) is selected because F36 sand is used as the test material. The selected calibration function gives the gravimetric moisture content.



In the menu "Test", the window "Test in Mode A" is selected. The mode A will only work if a calibration function has been activated.

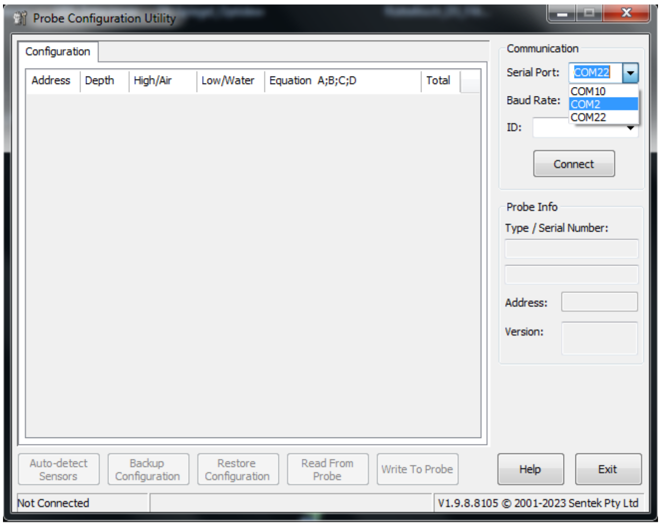


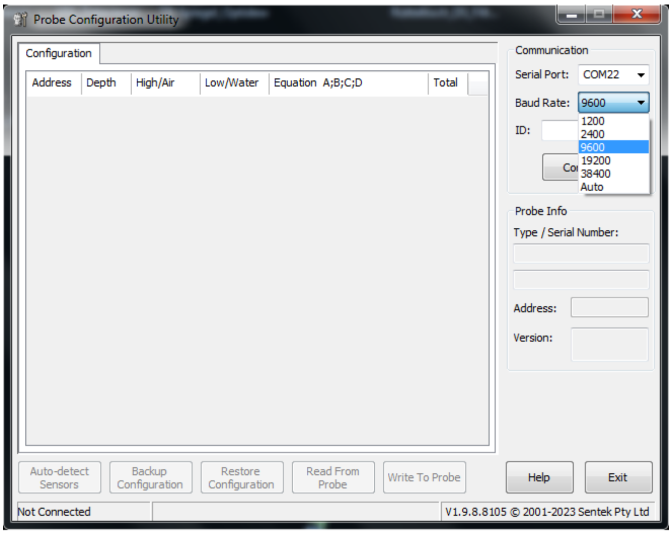
The values "Moist" correspond to the soil moisture content.

"MatTemp" is temperature.

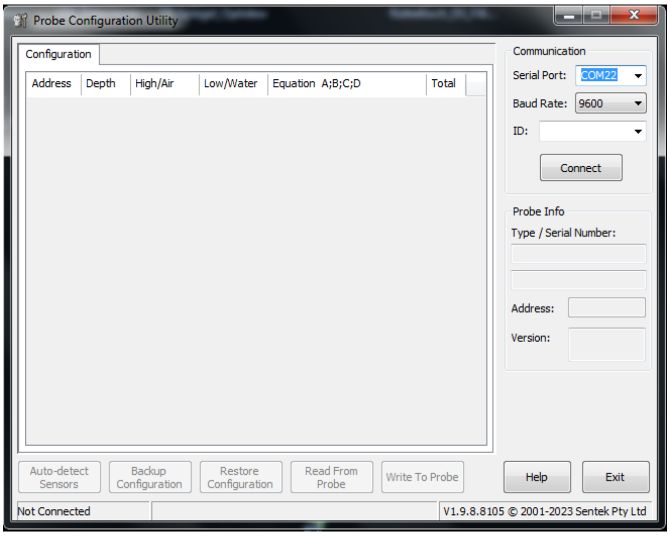
"tp" is the radar time which corresponds to the respective moisture value

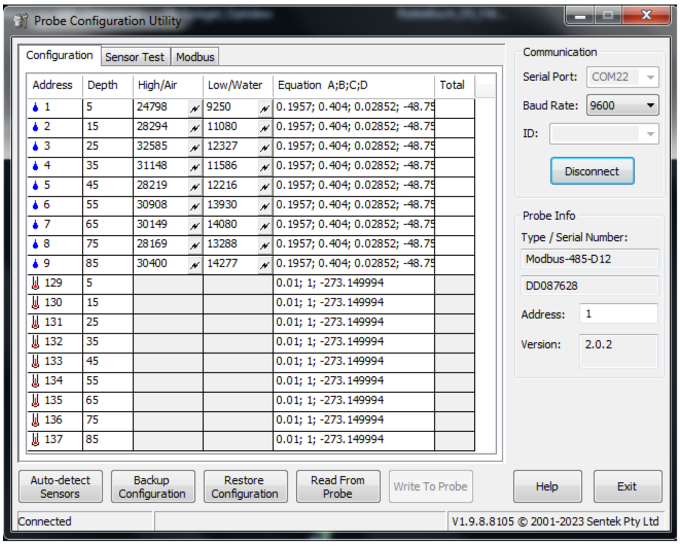
Drill and Drop:





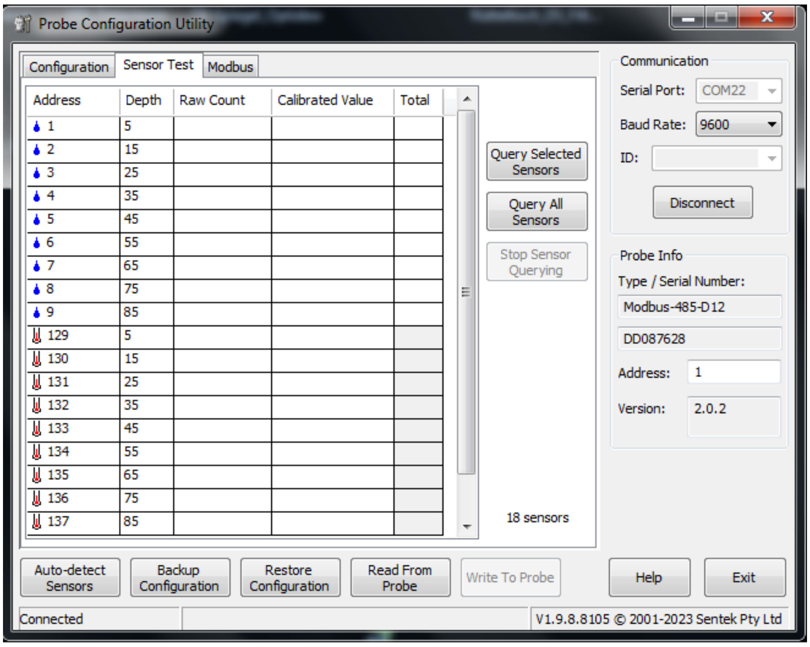
In the menu “Configuration” and the window “Communication”, an available serial port and preferred baud rate are selected. The “Probe Info” gives information about the probe type and serial number, address and version of the probe.





After selecting the serial port and baud rate, the sensor is activated by clicking the “Connect” button. Once the sensor is connected, the values in the configuration page are displayed accordingly.

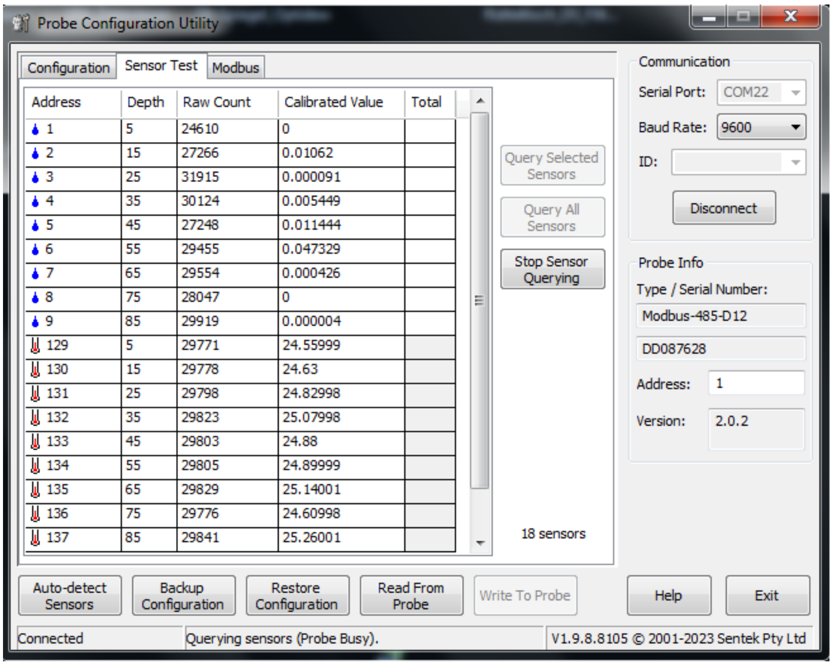
The configuration page is for displaying and editing the sensor configuration. The Address displays the address of each sensor within the probe. The Depth shows the depth of each sensor located at a 10cm interval from each other. High/Air is used for taking new air counts and Low/Water is used for taking new water counts when the sensor needs to be normalized. Equations A, B, C, and D are the calibration equation for the sensor. Drill & Drop does not have material specific calibration so a general calibration equation is used for all soil types. The fourth value (D) is the temperature compensation value for the soil moisture sensor.



The “Sensor Test” window shows the information on all moisture and temperature sensors.

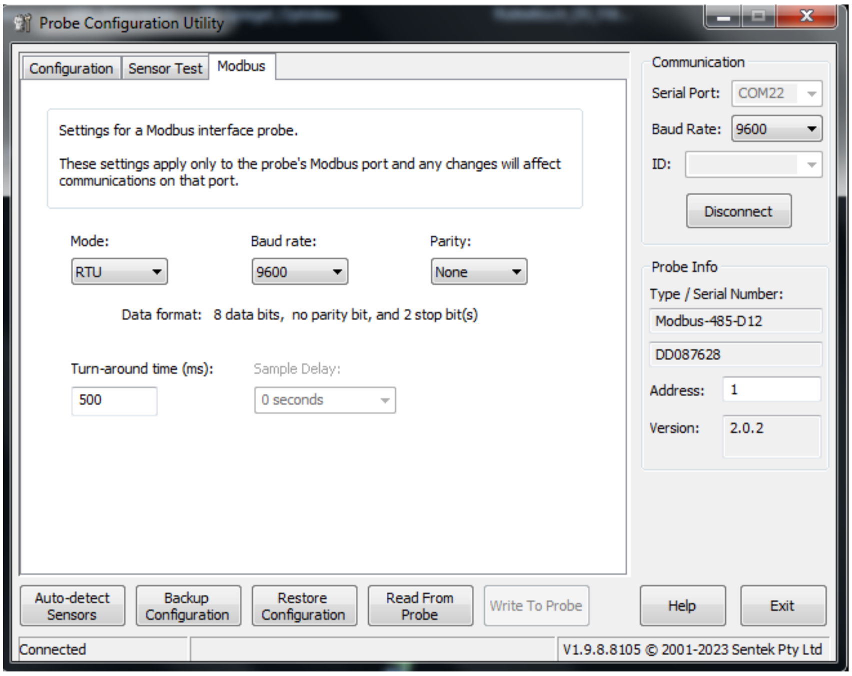
“Query Selected Sensors” is used when only a number of sensors are being activated.

“Query All Sensors” is used when all sensors need to be activated.



The sensor keeps reading the soil moisture content and soil temperature until the “Stop Sensor Querying” button is clicked and the readings stop.

It is not possible to save the sensor readings to a file directly from the software.



The settings of the Modbus port such as the mode, baud rate, and parity can be changed in this window.

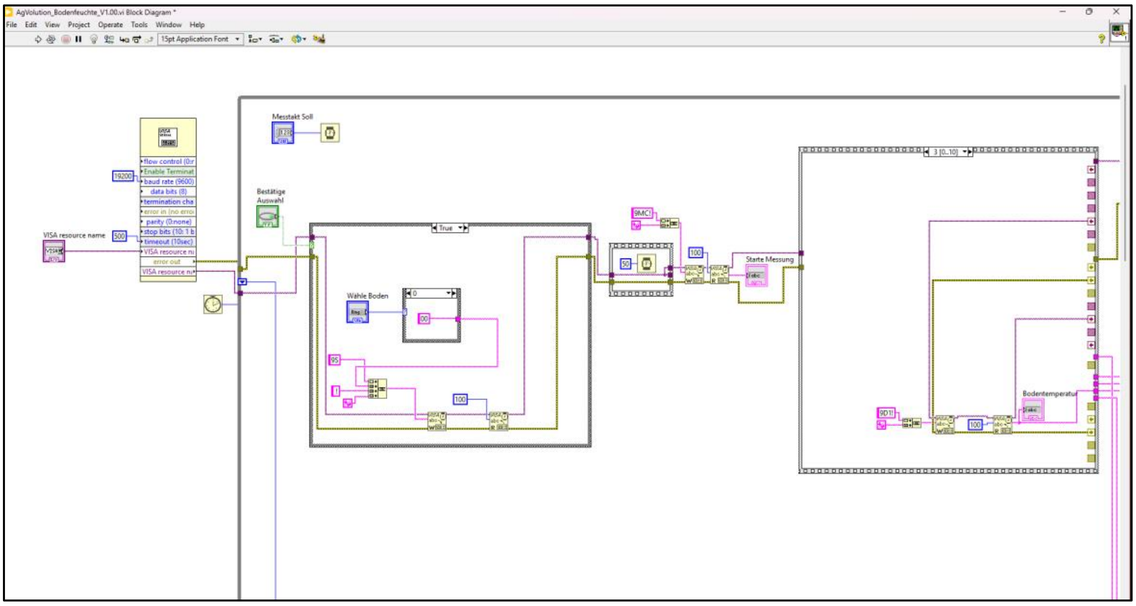
There are five control buttons along the bottom and their functions are listed below:

- Auto-detect Sensors: this is the starting point of a new probe or after altering the configuration, this button is used to detect the sensors.
- Backup Configuration: allows to save displayed configuration settings or changes made to a configuration (*.cfg) file.
- Restore Configuration: allows loading of previously backed up configuration settings from a configuration (*.cfg) file.
- Read From Probe: reads in the sensor configuration from the probe and displays it in the lists.
- Write To Probe: sends all the new probe settings from the Probe Configuration Utility to the Probe. All old configurations would be overwritten.

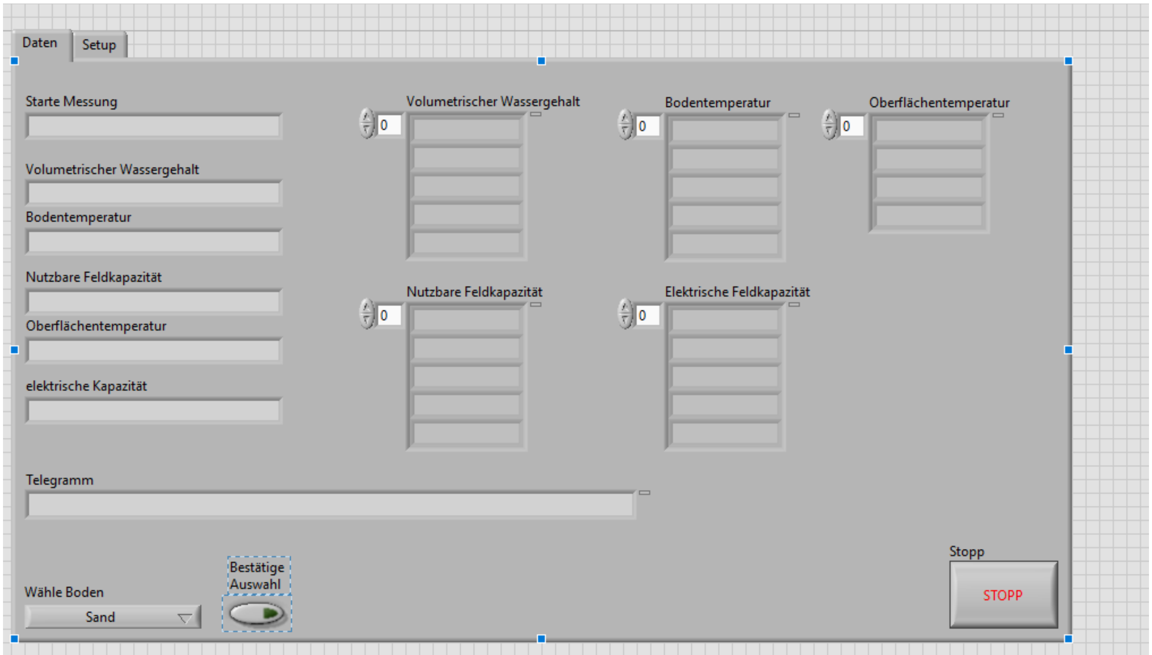
The status bar on the bottom line is for displaying the connection status, general status, and version number of the probe.

Climavi:

Software for Climavi sensor was built using LabVIEW.



The user interface:



There are five calibration functions according to the manufacturer:

- Sand
- Silt
- Clay
- Sandy loam
- Clayey loam

The calibration function “Sand” was selected for the experiment.

Performance criteria

- **Accuracy:** this was tested by comparing the sensor readings to the reference value
- **Precision:** this was tested by examining the consistency in repeated measurements under the same conditions
- **Ease of use:** this was tested by observing the ease of installation, operation and data retrieval process
- **Sensitivity:** this was tested by examining how well the sensor read extremely dry and extremely wet moisture conditions

Statistical analysis

The performance of the soil moisture sensors was evaluated using Root Mean Square Error (RMSE), Index of Agreement (IA), and Mean Bias Error (MBE)[9].

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(M_i - P_i)^2}{N}}$$

$$\mathrm{IA} = 1 - \frac{\sum_{i=1}^{n}(M_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{M}| + |M_i - \bar{M}|)}$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(P_i - M_i)}{N}$$

Where N is the sample size, M is the measured (reference) value, P is the predicted (sensor) value, $\overline{M}$ is the average measured value. The units for RMSE and MBE are volumetric water content (cm^3cm^{-3}), and IA is dimensionless. A range of IA lies between 0 and 1, and a value of 0 indicates no agreement between the measured and predicted values. A value of 1 indicates perfect agreement between measured and predicted values. Hignett and Evett (2008)[10] discussed that for most agricultural and research applications, the measurement accuracy needs to be within 0.01 – 0.02 cm^3cm^{-3}. Researchers therefore assess the performance and accuracy of soil moisture sensors using the following criteria: MBE ± 0.02 cm^3cm^{-3}, RMSE < 0.035 cm^3cm^{-3} and IA > 0.8.

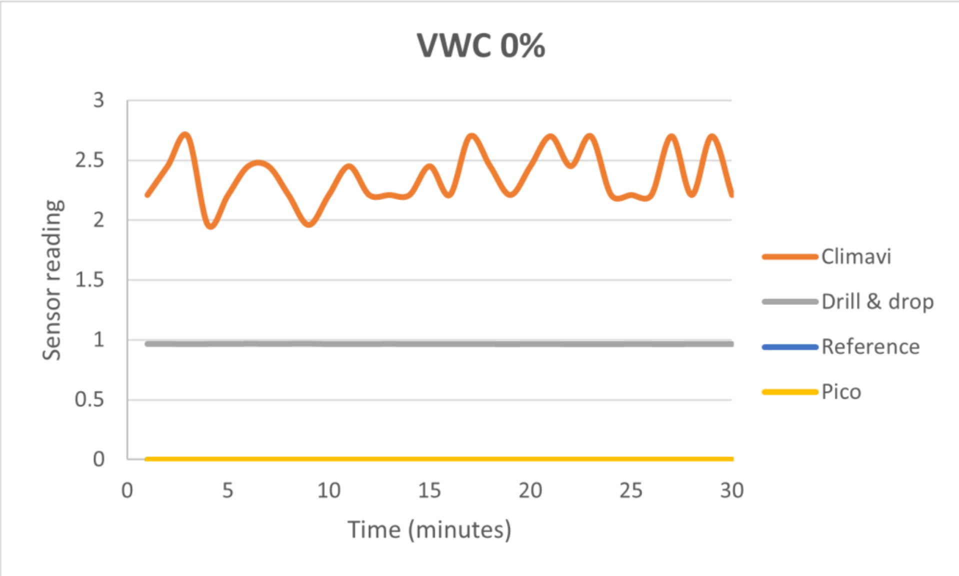
Uncertainty Budget

The uncertainty budget is calculated for the reference volumetric content used during the laboratory test. The reference volumetric water content, Θv is calculated using the following parameters: volume of soil, mass of dry soil, mass of wet soil. These various measurements have contributions to the total measurement error.

Results and Discussion

Comparing sensors output in extremely dry conditions

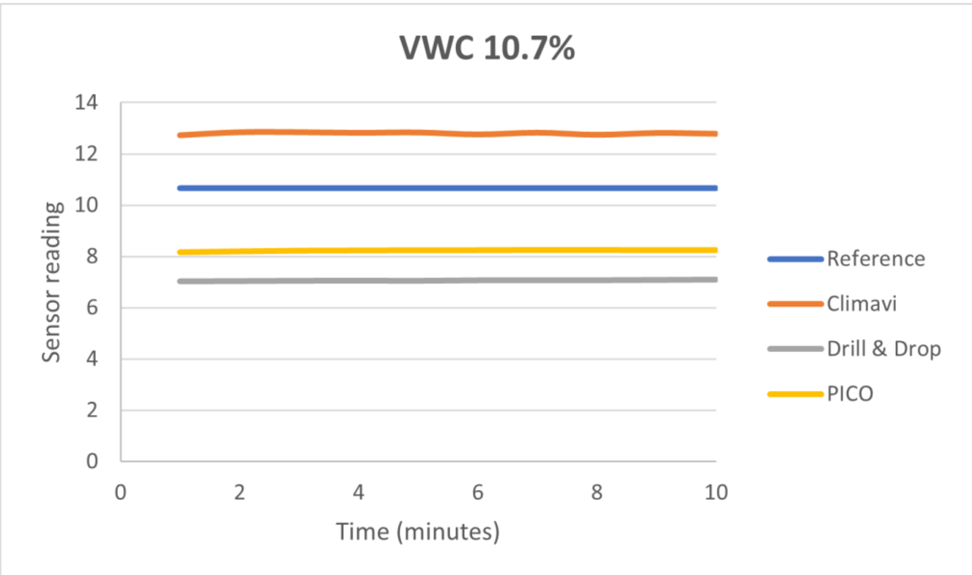
The sensors were inserted into dry sand, their readings were taken and compared to the volumetric water content of dry sand which is 0%.



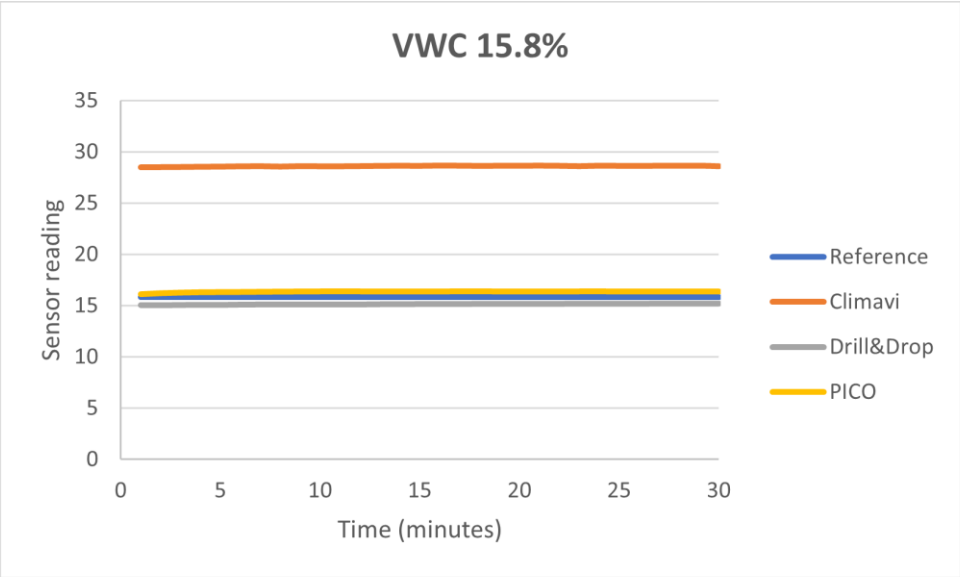
At volumetric water content (VWC) of 0%, PICO sensor measured the soil moisture content accurately with no deviation from the reference. Drill & Drop overestimated the water content (0.966%) with a low standard deviation of 0.00096%, while Climavi showed the highest overestimation (2.355%) of the VWC with standard deviation of 0.2%. Climavi sensor has a lot of noise in the measurements indicating that the sensor does not give consistent readings in very dry conditions.

Comparing sensors output over a range of moisture conditions

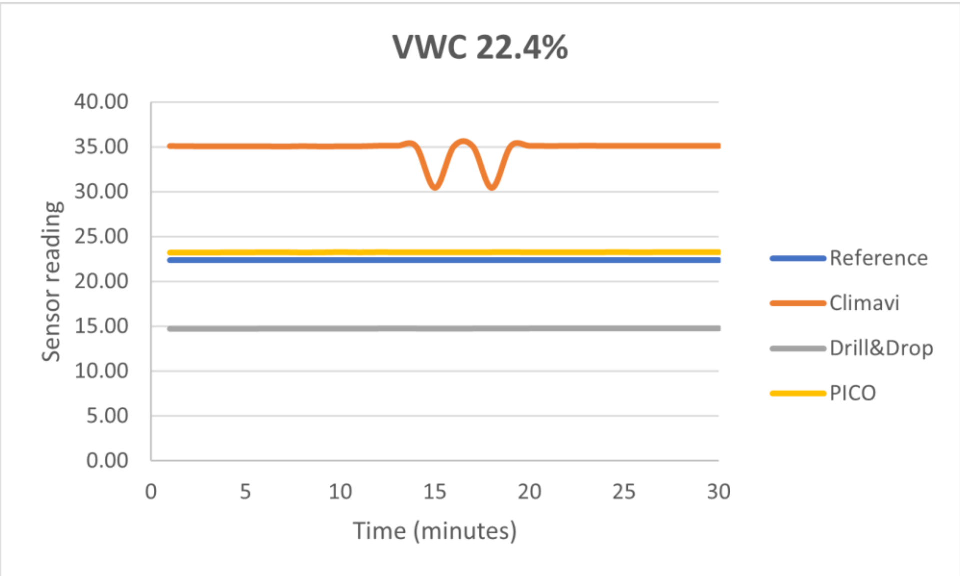
The sensors were used to take readings over five different soil moisture contents (10%, 15%, 20%, 25%, 30%) in sand:



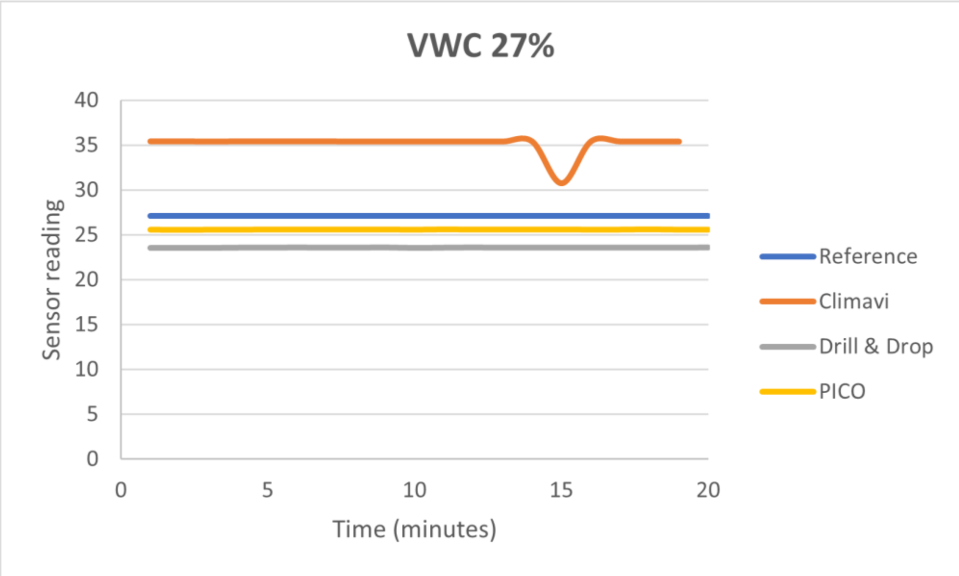
At volumetric water content (VWC) of 10.7%, all sensors show deviation from the reference. PICO and Drill & Drop underestimates soil moisture content by approximately 2% and 4% respectively, while Climavi overestimates by approximately 3%. Drill & Drop readings had the lowest standard deviation (0.019) while Climavi sensor readings had the highest standard deviation (0.04) among the three sensors.



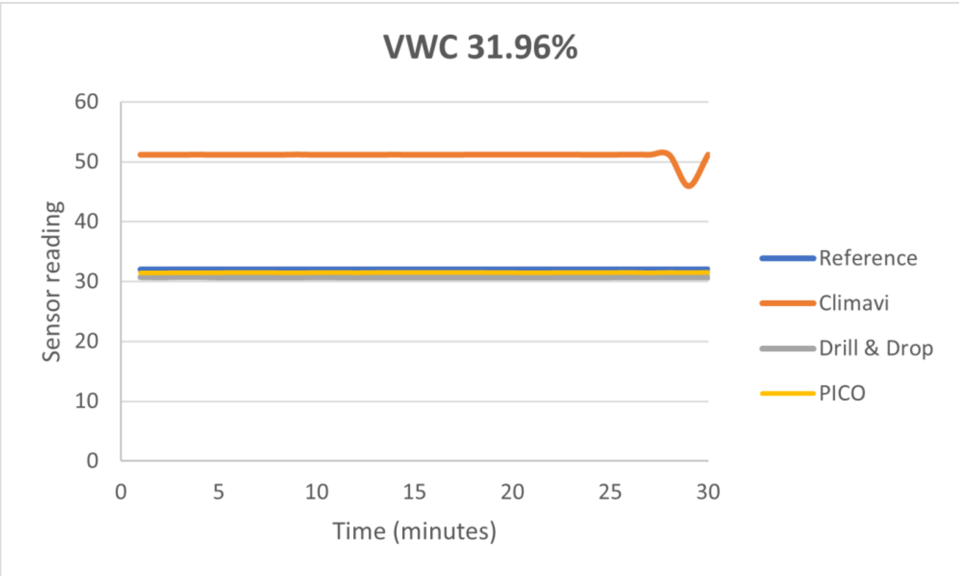
At volumetric water content (VWC) of 15.8%, PICO sensor overestimates the VWC by 0.5%. This is within the accuracy band of ± 1% promised by the manufacturer. Drill & Drop underestimates the VWC by 0.7%, while Climavi sensor overestimates the VWC by 13%.



At volumetric water content of 22.4%, PICO and Climavi sensor overestimates the VWC by 0.9% and 12.4% respectively, while Drill & Drop underestimates by 7.6%. Pico and Drill & Drop readings have a standard deviation of 0.01. Climavi has the highest standard deviation (1.19) and there is noise in the measurements as seen in the graph above.



At volumetric water content of 27%, PICO sensor underestimates VWC by 1.45%. Drill & Drop underestimates by 3.5%, while Climavi overestimates by 8%. Pico and Drill & Drop readings have reasonably low standard deviations. Climavi has the highest standard deviation (1.05) amongst the three sensors and the readings show some noise.



At volumetric water content of 31.96%, PICO sensor underestimates the VWC by 0.45%. Drill & Drop underestimates by 1.23%, while Climavi overestimates by 19%. Climavi also has the highest standard deviation (0.95) and shows some noise towards the end of the measurements.

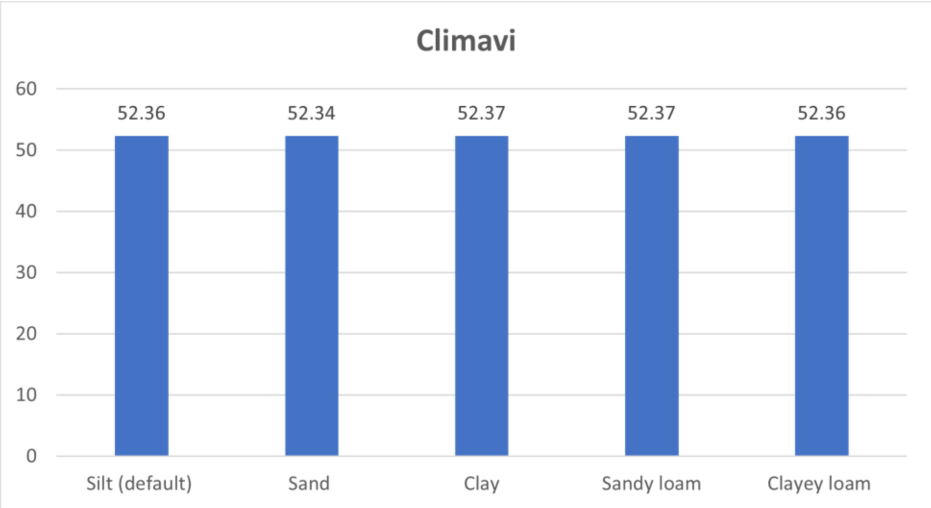
Assessing the Effectiveness of Material-Specific Calibration Functions

The effectiveness of material-specific calibration functions was evaluated for three soil moisture sensors. Each sensor offers different calibration capabilities:

- PICO Sensor: Offers over six calibration functions for material-specific measurements.
- CLIMAVI Sensor: Provides five calibration functions for major soil types.
- Drill & drop Sensor: Has only one general calibration function.

Test 1: Climavi Sensor Calibration Effectiveness

To assess the effectiveness of the Climavi calibration functions, the sensor calibration was changed while the measuring conditions remained constant.

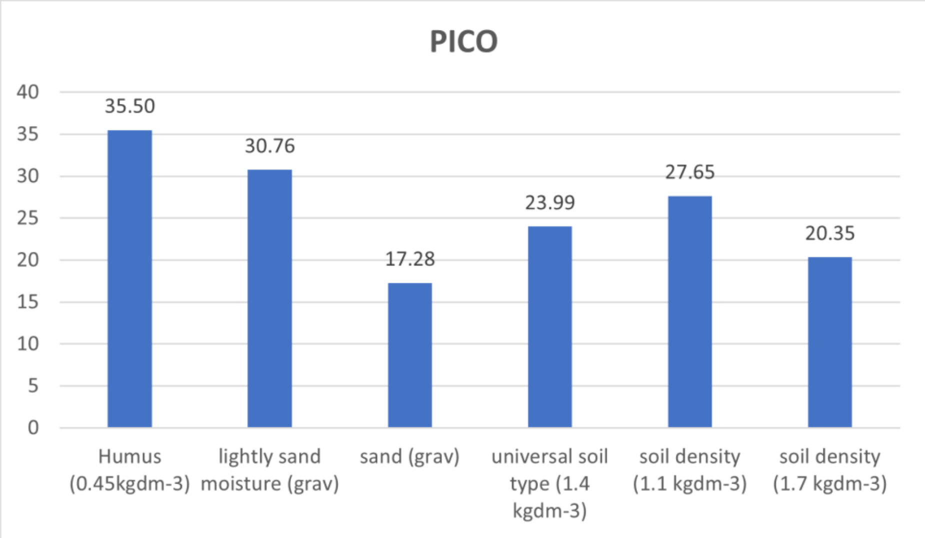


Results:

- For CLIMAVI, there was no significant difference in sensor output when the soil type was changed from Silt (default) to Clayey loam. All the values remain within a narrow range from 52.34% – 52.37%.
- Defining the soil type as "Sand" did not increase the sensor accuracy, indicating that the calibration functions for different soil types did not significantly affect the sensor output.

Test 2: PICO Sensor Calibration Effectiveness

To assess the effectiveness of PICO sensor calibration functions, the sensor calibration was changed multiple times while the measuring conditions remained constant.



Results:

- For PICO, the calibration function had a strong influence on the sensor output. Depending on the soil texture and soil density, the PICO sensor provided a wide range of values from 17.28% - 35.50%.
- Setting the soil type as "Sand" had a significant influence on the sensor output and overall performance. However, it is important to note that the readings for "Sand" and "Lightly Sand moisture" are gravimetric water content readings, while the other calibration functions provide values for volumetric water content.
- To convert the values of sand to volumetric water content, the following formula is used:

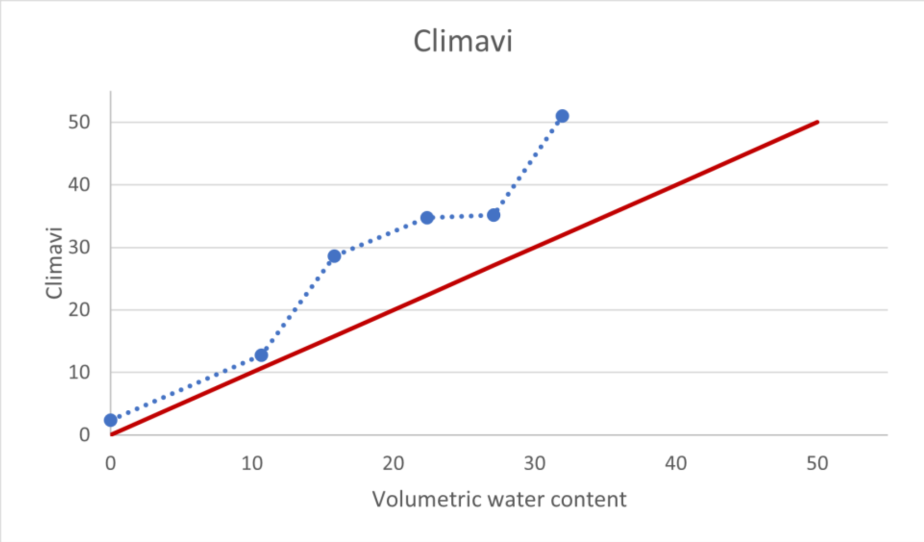
$$\emptyset v = \emptyset g \times \frac{\rho_{soil}}{\rho_{water}}$$

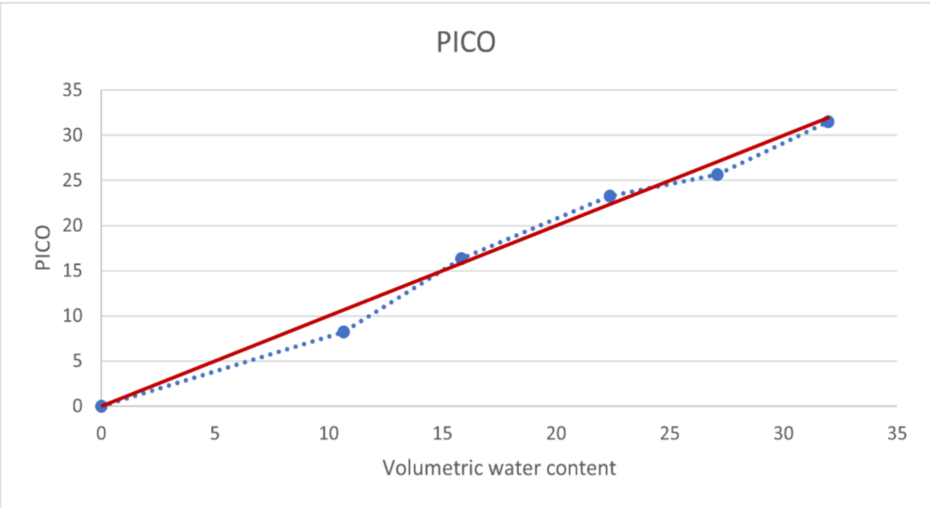
where;
Θv = volumetric water content
Θg = gravimetric water content
ρ_{soil} = bulk density of soil
ρ_{water} = density of water ($1 g/cm^3$)

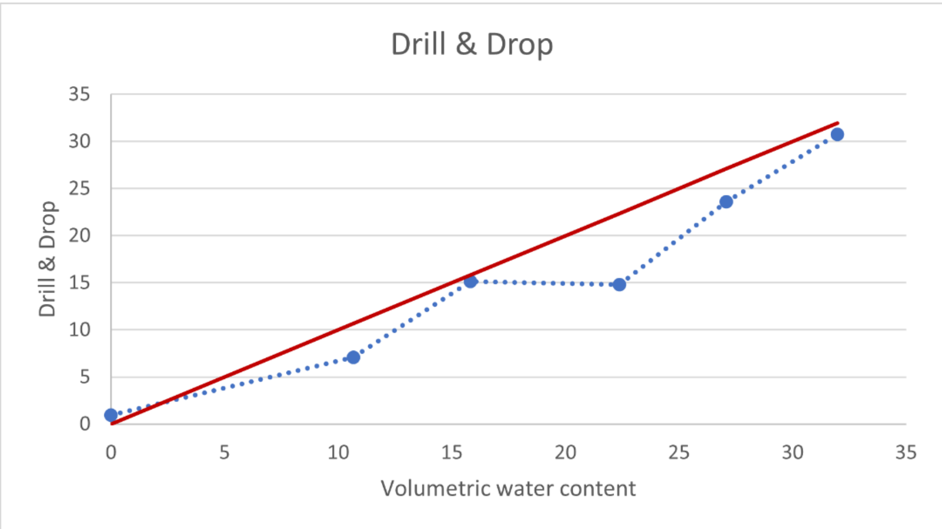
In conclusion, the calibration functions for different soil types did not significantly affect CLIMAVI sensor output, suggesting limited effectiveness in improving sensor accuracy through calibration function adjustments.

On the other hand, the calibration functions of PICO sensor had a notable impact on the sensor output, demonstrating the importance of selecting the appropriate calibration function based on soil type and density. This highlights PICO sensor's ability to provide more accurate and tailored measurements when properly calibrated.

Visualizing Soil Moisture Sensor Readings in comparison to the reference line







Accuracy Evaluation of Soil Moisture Sensors

The soil moisture sensors have been evaluated for their accuracy based on Regression analysis, Root Mean Square Error (RMSE), Mean Bias Error (MBE), and Index of Agreement (IA). The soil moisture sensors are assessed using the following accuracy criteria: MBE ± 0.02 cm^3cm^{-3}, RMSE < 0.035 cm^3cm^{-3}, IA > 0.8 and R^2 > 0.65.

Regression R^2

The regression R^2 is a measure of the strength of the linear relationship between the sensor readings and the reference volumetric water content. PICO has the highest correlation (0.9886), followed by CLIMAVI (0.9490) and Drill & drop (0.9356).

Slope

The slope indicates how much the dependent variable tends to change with a unit increase in the independent variable. PICO has a slope close to 1 indicating nearly perfect proportionality with the reference values. Drill & drop tends to under-estimate the volumetric water content (slope < 1), while CLIMAVI tends to over-estimate (slope > 1).

Intercept

This is the expected value of the dependent variable when the independent variable is zero. PICO and Drill & drop have negative intercepts which indicates a slight underestimation bias while CLIMAVI has a positive intercept, indicating an overestimation bias.

Root Mean Square Error (RMSE)

This metric quantifies the average magnitude of the errors between the reference value and the sensor readings. PICO has the lowest RMSE value of 0.012 cm^3cm^{-3} indicating highest accuracy, followed by Drill & drop with an RMSE of 0.038 cm^3cm^{-3} indicating moderate accuracy, and CLIMAVI has the largest error with an RMSE of 0.112 cm^3cm^{-3} indicating the least accuracy amongst the three sensors.

Sensor	R^2	Slope	Intercept	RMSE ($cm3cm^{-3}$)	MBE ($cm3cm^{-3}$)	Index of Agreement
PICO	0.9886	1.0012	-0.5127	0.012445	-0.0049	0.996608
Drill & drop	0.9356	0.8938	-0.70413	0.037871	-0.02614	0.96696
CLIMAVI	0.9490	1.4543	1.303866	0.11226	0.094748	0.842493

Converting RMSE and MBE from % to cm^3cm^{-3} involves dividing by 100

Mean Bias Error (MBE)

This metric indicates the average bias in predictions with negative values indicating underestimation and positive values indicating overestimation. PICO and Drill & drop have negative MBE values of -0.0049 cm^3cm^{-3} and -0.0261 cm^3cm^{-3} respectively, indicating an underestimation bias in their measurements. However, Drill & drop has a larger bias for underestimation. CLIMAVI has a high positive MBE of 0.0947 cm^3cm^{-3}, indicating a strong bias for overestimation.

Index of Agreement (IA)

A range of IA lies between 0 and 1, and a value of 0 indicates no agreement between measured (reference) and predicted (sensor) values. A value of 1 indicates a perfect fit of observed to predicted values. The higher value of IA indicates better agreement between observed and predicted values. PICO shows the highest IA (0.997), followed by Drill & drop (0.967), then CLIMAVI (0.842).

Precision Evaluation of Soil Moisture Sensors

Three soil moisture sensors – PICO, Drill & drop, CLIMAVI – have been evaluated for their precision under varying soil moisture contents (0%, 10%, 15%, 20%, 25%, 30%). Precision is assessed using the coefficient of variation (CV) metric. To calculate this, 30 readings are taken per sensor at each moisture level under stable measurement conditions.

Coefficient of Variation (CV)

The Coefficient of Variation (CV) is a statistical measure of the dispersion of data points around the mean in a data series. It is expressed in percentage and is useful for comparing variability amongst different data series. Lower CV values indicate greater consistency and precision in the sensor readings.
The formula for CV is as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

$$\mathrm{CV} = \left(\frac{\sigma}{\bar{x}}\right) \times 100$$

Where:

- σ = standard deviation
- x_i = individual sensor readings
- $\bar{x}$ = mean of the sensor readings
- CV = coefficient of variation

The table below presents the coefficient of variation for the sensors across varying volumetric water content (VWC) measurements:

VWC (%)	PICO	Drill & drop	CLIMAVI
0	0	0.09	9.30
10	0.34	0.27	0.34
15	0.36	0.30	0.16
20	0.05	0.03	3.42
25	0.03	0.01	2.98
30	0.06	0.04	1.87

The PICO sensor exhibits coefficient of variation (CV) values ranging from 0% to 0.36%. These low CV values indicate that PICO provides consistent and precise measurements, highlighting its high precision.

The Drill & drop sensor shows coefficient of variation (CV) values between 0.01% and 0.30%. The narrower range of CV values compared to PICO suggests that Drill & drop has a slightly higher precision.

The CLIMAVI sensor presents a broader range of CV values, from 0.16% to 9.30%. This indicates that CLIMAVI is the least precise among the three sensors. The high variability of Climavi sensor at VWC 0% (9.30) suggest significant inconsistency in its readings in very dry conditions.

Among the three sensors evaluated, the Drill & drop sensor demonstrates highest precision due to its narrow range of CV values. The PICO sensor also shows high precision but with a slightly higher range of CV values. The CLIMAVI sensor, however, exhibits considerable variability in its measurements, making it the least precise sensor in this evaluation.

Comparative Evaluation and Ranking of Soil Moisture Sensors

Based on the evaluation of precision and various performance metrics, the soil moisture sensors are ranked from 1st to 3rd. The strengths and weaknesses of the sensors are presented below:

1. **PICO Sensor**

   Strengths:

   - Highest R^2 (0.9886), indicating a very strong linear relationship with the reference values.
   - Slope close to 1 (1.0012), showing nearly perfect proportionality with reference values.
   - Lowest RMSE (0.012 cm^3cm^{-3}), indicating highest accuracy.
   - Highest IA value (0.996608), indicating best agreement between predicted (sensor) and observed (reference) values.
   - Lowest CV value (0%) and narrow range of CV values (0% - 0.36%), indicating high consistency in measurements.

   Weaknesses:

   - Slight negative intercept (-0.5127) and MBE (-0.0049 cm^3cm^{-3}), indicating minor underestimation.

   Conclusion:

   - The PICO sensor has an RMSE (0.012 cm^3cm^{-3}) value that is smaller than the defined criteria for assessing sensors performance i.e., RMSE < 0.035 cm^3cm^{-3} and an MBE (-0.0049 cm^3cm^{-3}) value within the acceptable range of MBE ± 0.02 cm^3cm^{-3}. The PICO sensor can therefore be categorized as accurate based on these metrics.

- The PICO sensor is the most reliable and accurate, making it the best choice for precise measurements.

2. **Drill & Drop Sensor**

   Strengths:
   - Good R^2 (0.9356) and IA values (0.96696), indicating reliable performance.
   - Narrow range of CV values (0.01% - 0.30%), indicating high consistency in measurements.

   Weaknesses:

   - Slope less than 1 (0.8938), suggesting slight under-prediction.
   - Moderate RMSE (0.038 cm^3cm^{-3}), indicating moderate accuracy.
   - Significant negative MBE (-0.0261 cm^3cm^{-3}), indicating consistent underestimation bias.

   Conclusion:

   - The Drill & drop sensor has an RMSE (0.038 cm^3cm^{-3}) value greater than the defined criteria i.e., RMSE < 0.035 cm^3cm^{-3} and the MBE (-0.0261 cm^3cm^{-3}) value is also out of the acceptable range for agricultural applications i.e., MBE ± 0.02 cm^3cm^{-3}.
   - The difference between the accuracy metrics of Drill & drop and the defined criteria is not wide, indicating that the Drill & drop sensor performs well overall. This performance is commendable since the sensor does not have any material specific calibration.
   - The Drill & Drop sensor tends to under predict soil moisture content, and its readings has some error that might need correction. This sensor can be improved by material-specific calibration.

3. **CLIMAVI Sensor**

   Strengths:
   - Decent R^2 (0.9490), indicating reasonable agreement with reference values.

   Weaknesses:

   - Slope significantly greater than 1 (1.4543), indicating over-prediction.
   - Highest RMSE (0.112 cm^3cm^{-3}), indicating least accuracy.
   - Highest MBE (0.0947 cm^3cm^{-3}), indicating a strong bias for overestimation.
   - Lowest IA value (0.842493), indicating least agreement between predicted (sensor) and measured (reference) values.
   - Highest CV range (0.16% - 9.30%), indicating least consistency in measurements.

Conclusion:

- The CLIMAVI sensor has RMSE (0.112 cm^3cm^{-3}) and MBE (0.0947 cm^3cm^{-3}) values that are significantly higher than the acceptable thresholds for soil moisture sensors i.e., RMSE < 0.035 cm^3cm^{-3} and MBE ± 0.02 cm^3cm^{-3}.
- The CLIMAVI sensor shows the least accuracy and precision among the three sensors evaluated.
- It is possible that the container used to test the sensors had a volume smaller than the sensor measuring volume. This could have contributed to the magnitude of errors in CLIMAVI's measurement.
- On the other hand, the soil-specific calibration equations did not have significant impact on the sensor's results, this points to a possible defect in factory-provided calibration equations.
- The CLIMAVI sensor needs to be tested further and evaluated to understand the sources of error.

References

1. Dong, Y., Miller, S., & Kelley, L. (2020). Performance evaluation of soil moisture sensors in Coarse- and Fine-Textured Michigan Agricultural soils. *Agriculture*, *10*(12), 598. https://doi.org/10.3390/agriculture10120598
2. Varble, J., & Chávez, J. (2011). Performance evaluation and calibration of soil water content and potential sensors for agricultural soils in eastern Colorado. Agricultural Water Management, 101(1), 93–106. https://doi.org/10.1016/j.agwat.2011.09.007
3. Vaz, C. M., Jones, S., Meding, M., & Tuller, M. (2013). Evaluation of standard calibration functions for eight electromagnetic soil moisture sensors. Vadose Zone Journal, 12(2), 1–16. https://doi.org/10.2136/vzj2012.0160
4. Nieberding, F., Huisman, J. A., Huebner, C., Schilling, B., Weuthen, A., & Bogena, H. R. (2023). Evaluation of three soil moisture profile sensors using laboratory and field experiments. Sensors, 23(14), 6581. https://doi.org/10.3390/s23146581
5. Hrisko, Joshua. (2020). Capacitive Soil Moisture Sensor Theory, Calibration, and Testing. 10.13140/RG.2.2.36214.83522.
6. Agvolution_GmbH_Kurzübersicht_Climavi_Soil
7. Sentek Drill & Drop Probe Manual V1.5
8. Manual_TRIME-PICO64-321
9. Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63, 1309–1313
10. Hignett, C., Evett, S., 2008a. Direct and surrogate measures of soil water content. In: Evett, S.R., Heng, L.K., Moutonnet, P., Nguyen, M.L. (Eds.), Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria, ISSN 1018-5518.