

APPLICATION OF STATISTICAL TECHNIQUES FOR TESTING SOIL MOISTURE MEASUREMENT WITH STAINLESS STEEL TUBE SENSORS

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Abstract

Soil moisture measurement with advanced analytical tools is expensive and complicated. A simple soil moisture sensor was created using the capacitance between two parallel rods, which can be measured using stainless steel tubes. The statistical significance of differences in measurement testing requires studies. In this work, we introduced analysis of variance and correlation approaches to assess the statistical significance of differences between systematic effects and errors resulting from environmental parameter variation. Comparisons of the obtained results with effects and errors resulting from environmental parameter variation data on the capacitance between the two parallel rod sensors were presented. This statistically significant approach contributes to efficient and low-cost estimations of soil moisture and understandings of soil moisture based on environmental parameters.

Keywords: Analysis of Variance; Correlation analysis; Soil Moisture; Stainless Steel Tubes Sensor; Statistical significance

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Introduction

A key element to understanding the nature of global change is the ability to model the two-way interaction between land and atmosphere. Perhaps the most important role that the land surface component performs is the partitioning of incoming radiative energy into sensible and latent heat fluxes. There have been a number of modeling studies, demonstrated the sensitivity of soil moisture anomalies to climate (Walker and Rowntree, 1977; Delworth and Manabe, 1988) Shukla (personal communication) for instance, reports that soil moisture is the second most important forcing function, second only to the sea surface temperature in the mid-latitudes, and it becomes the most important forcing function in the summer. The role of soil moisture is equally important at smaller scales. Recent studies with mesoscale atmospheric models have similarly demonstrated, sensitivity to spatial gradients of soil moisture. For example, Fast and McCorcle (1991) have shown that moisture gradients can induce thermally induced circulations similar to sea breezes. Chang and Wetzel (1991) have concluded that the spatial variations of vegetation and soil moisture affect the surface baroclinic structures through differential heating which in turn indicate the location and intensity of surface dynamic and thermodynamic discontinuities necessary to develop severe storms. In yet another study, Lanicci *et al.* (1987) have shown that dry soil conditions over the southern Great Plains can dynamically interact to alter pre-storm conditions and subsequent convective rainfall patterns. More recently, Betts *et al.* (1994) demonstrated that the initialization of the Global Climate Model Weather Forecast (GCMWF) weather predictions with current soil moisture values can lead to improved rainfall predictions. In addition to the role of soil moisture in the interactions between the land surface and the atmosphere, soil moisture is a storage of water timewise between rainfall and evaporation that acts as a regulator to one of the more fundamental hydrologic processes, infiltration and runoff production from rainfall and which must be accounted for in any water and energy balances. Soil moisture content may be determined via its effect on dielectric constant by measuring the capacitance between two electrodes implanted in the soil (Gardner, 1986; Bell *et al.*, 1987; Dean *et al.*, 1987; Halbertsma *et al.*, 1987). Where soil moisture is predominantly in the form of free water (e.g., in sandy soils), the dielectric constant is directly proportional to the moisture content (Malicki and Hanks, 1989; Malicki *et al.*, 1989). The probe is normally given a frequency excitation to permit

measurement of the dielectric constant. The probe is normally given a frequency excitation to permit measurement of the dielectric constant. The readout from the probe is not linear with water content and is influenced by soil type and soil temperature (Mckim *et al.*, 1980). Therefore, careful calibration is required and long-term stability of the calibration is questionable and expensive cost. So, this modeling approach in this research contributes to efficient and low-cost for developed system has been processed with microcontroller estimations of soil moisture estimations and understandings of the soil moisture based on environmental parameters. In soil moisture measuring system, type of soil moisture sensor was developed using stainless steel tubes. The electrical contact resistance of stainless steel arises as the result of the dense protective oxide layer. The measurement of the soil moisture by advanced analytical instruments is costly and difficult. In this work, we introduced analysis of variance and correlation approaches to assess the statistical significance of differences between systematic effects and errors resulting from environmental parameter variation. Comparisons of the obtained results with effects and errors resulting from environmental parameter variation data on capacitance between the two parallel rod sensors were presented. This statistically significant approach contributes to efficient and low-cost estimations of soil moisture and understandings of soil moisture based on environmental parameters.

Materials and Methods

A Basic Explanation of the Analysis of Variance (ANOVA)

ANOVA determines significance by calculating the ratio of variance estimates from sample means and values (Krzywinski and Altman, 2014). Their ratio or test statistic F can be used between group mean squares (MS_B) and within group mean squares (MS_W), which are calculated from between treatment sum of squares (SS_B) and within treatment sum of squares (SS_W) weighted by degrees of freedom (d.f.). The degrees of freedom (d.f.) indicate the number of independent deviations in the treatment sum of squares (SS); nevertheless, the deviations are not all independent because a quantity's departures from its own mean must total zero. The ANOVA null hypothesis states that all samples come from the same distribution and have equal means. Under this null, the group variance of sample means and the within-group variation of

sample values are predictably linked. We introduced the concept of partitioning variance within group variance, which was regarded as experimental error, and between group variance as structural and topological parameter variation. In a one-way ANOVA, the relevant quantities are within group variance and between group variance. Within-group variance corresponds to variance in the sample after other sources of variation have been accounted for and represents experimental error. If some sources of error are not accounted for (e.g., structural and topological parameter variation), within-group variance will be inflated. Between-group variance is another estimate for within-group variance, additionally inflated by the average squared deviation of treatment means from the grand mean. As noise within samples drops, a larger fraction variation is allocated between group variances, and the power of the test improves (Armstrong *et al.*, 2002). This shows that it is advantageous to reduce within-group variance. We can accomplish this by identifying and isolating likely sources of sample variability.

Design and Details

At predetermined depths in the access tube, the probe's sensor unit is fitted with PVC extension tubes of the same diameter as the sensor casing and 200 mm in length. The exterior case diameter is 40 mm, and the 100-mm-long probe tubes have a diameter of 5 mm each. The top cap of the probe housing's sensor unit is attached to the fiber transmitter and supports the printed circuit board, which connects to the capacitance between two parallel rods, which may be measured using stainless steel tubes mounted in the tubular outer case. The sensor on-off switch is located on the printed circuit board and operated by 12 volts of direct current from the fiber transmitter, which captures voltage change data using digital multimeters.

Principals of Operation

The configuration described here, with the sensor put into the access tube, measures the capacitance of the electrode system with a dielectric composed of the in-situ moist soil surrounding the access tube. The capacitor is part of the feedback loop of a modified frequency transistor oscillator that has a low temperature drift of roughly 0.33% per °C (0.5 MHz per °C). The probe outer casing, air volumes inside and between the probe and the access tube, the access tube wall, and the surrounding moist soil all contribute to the capacitance. The sole variable contribution is from the damp soil. The probe readout is connected to the sensor by cable, allowing operation in access tubes

up to a length of two meters. However, for the operation of frequencies in circuits, any distributed conducting system can be influenced by the capacitative effects of nearby bodies, such as the observer, so that a variable shift in frequency may result. Such factors can give an error equivalent to about 2 moisture vol%. The problem has been eliminated with this design; there are no conductors between the sensor and readout, and the probe is unaffected by the environment of the cable and the readout.

The Definition of Soil Water

Theoretical considerations indicate that the probe may respond to only a portion of the soil's total water content, presumably that which is least strongly held by surface absorption forces and surface tension, and thus there may be no direct general relationship between the electricity variable and water content as determined by the standard gravimetric method.

The gravimetric method of determining a soil's water content expresses the weight or volume of water ejected during oven-drying at 105°C per unit weight or volume. Surface tension forces hold water in unsaturated soil within pores of varying sizes and shapes. It is also found in thin layers on particle surfaces (especially clay minerals). The majority of this water is expelled by oven-drying at 105°C, along with water from the crystallization of some minerals (such as calcium sulfate minerals), volatile organic compounds, water stored in conjunction with hydrated oxides, and so on. Only the first category of water expelled by oven-drying (water held in pores by surface tension) is likely to contribute to the capacitance probe's frequency response, which is primarily determined by the number of water molecules free to relax as their dipoles respond to field reversals.

Proposed Method

Soil moisture measurement with advanced analytical instruments is costly and difficult. A simple soil moisture sensor was built using the capacitance of two parallel rods, which may be monitored with stainless steel tubes. The statistical importance of disparities in measurement testing necessitates research. In this study, we used analysis of variance and correlation techniques to determine the statistical significance of differences between systematic effects and errors caused by environmental parameter change. The acquired results were compared to the effects and inaccuracies caused by variations in ambient parameters on capacitance between the two parallel rod sensors. This statistically significant approach helps to estimate soil moisture efficiently and

affordably, as well as to comprehend soil moisture depending on environmental parameters.

Results and Discussion

This section is divided into 4 parts, as follows:

Part 1: Because ambient temperature influences the stability of the capacitor oscillator circuit (Dean *et al.*, 1987). Figure 1 and Table 1 provide data on temperature changes caused by environmental conditions every two minutes, six times (six replications), namely (A) pure water, (B) soil saturated with water (silky), (C) soil dehydrated by the weight or volume of water ejected after oven-drying at 105°C per unit weight or volume, and (D) room temperature. Statistics must be employed to evaluate the hypothesis of whether environmental temperature change is substantial enough to be regarded as statistically significant.

This part is divided into three steps, as follows:

Step 1: Prior to the variance analysis, we utilized the Kolmogorov-Smirnov test to determine if a set of raw data samples were picked at random from a population distributed under a normal curve, as per the assumptions of the parametric statistics in Figure 2.

The graph in Figure. 2 shows the test maximum statistic D of (a) water, (b) saturated soil, (c) dry soil, and (d) room equals 0.3079, 0.3163, 0.2590, and 0.1780, respectively, which had a trend lower than the critical test maximum statistic D, which equals 0.5219. In those results, it was assumed that the data distribution was not normal. In other words, the difference between the raw data sample and the normal distribution was not big enough to be statistically significant. For this reason, the raw data sample conflicted with the ANOVA under elements of the parametric statistical model (Siegel, 1956).

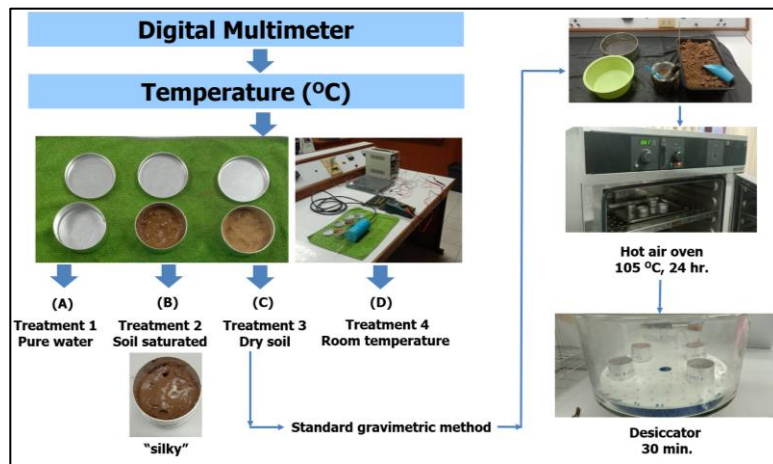


Figure 1. A pilot experiment was set up to collect data on temperature variations induced by environmental variables such as (A) clean water, (B) water-soaked soil (silky), (C) soil dehydrated using the conventional gravimetric method, and (D) room temperature

Table 1. The pilot experiment produced raw data on temperature fluctuations induced by environmental variables

Measurement replication	Temperature (°C)			
	Pure water	Soil saturated	Dry soil	Room
1	25.3	25.1	26.5	27.3
2	25.1	25.0	25.5	27.6
3	25.1	25.1	26.3	27.0
4	31.2	31.0	30.0	28.7
5	31.0	30.8	29.4	28.5
6	30.8	30.6	30.1	28.2
Maximum	31.2	31.0	30.1	28.7
Minimum	25.1	25.0	25.5	27.0
Average	28.1	27.9	28.0	27.9
S.D.	3.20	3.14	2.09	0.69
Median	28.1	27.9	28.0	27.9
Mode	25.1	25.1	-	-

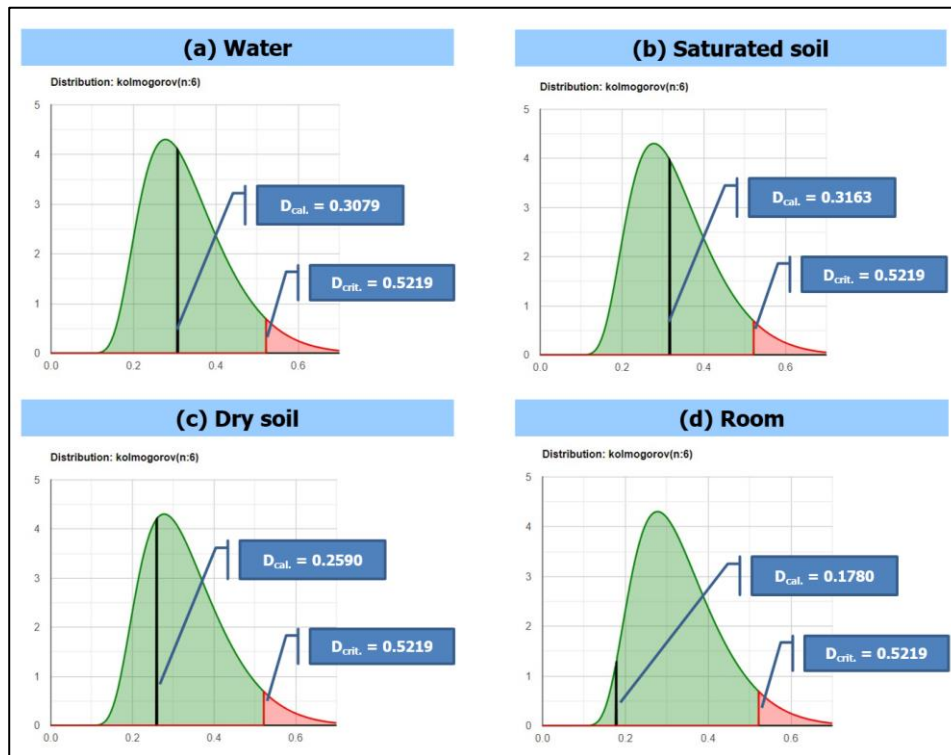


Figure 2. A test of the normality of temperature raw data changes was conducted using Kolmogorov-Smirnov, which was conducted on (a) water, (b) saturated soil, (c) dry soil, and (d) room

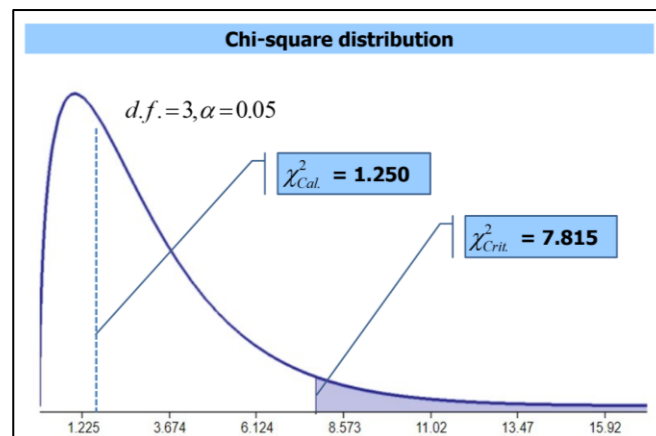


Figure 3. Nonparametric approach to the two-way ANOVA to compare four groups: (a) water, (b) saturated soil, (c) dry soil, and (d) room

Step 2: The procedure uses a nonparametric approach to the two-way ANOVA to compare three or more groups on a dependent variable that is measured on at least an ordinal level. It is sometimes called the Friedman Two-way Analysis of Variance by Ranks. The graph in Figure 3 shows the nonparametric approach to the two-way ANOVA to compare four groups: (a) water, (b) saturated soil, (c) dry soil, and (d) room. The test statistic

chi-square calculation equals 1.250, and the chi-square critical equals 7.815, which is in the 95% region of null hypothesis acceptance. This result means that the mean ranks of all groups are assumed to be equal. In other words, the difference between the mean ranks of all groups is not big enough to be statistically significant.

Step 3: Figure 3 shows the results of the Friedman two-way analysis of variance by rank,

Table 2. Spearman's Rank correlation coefficient of the relationship between environmental temperatures

			Temp. Water	Temp. saturated soil	Temp. dry soil	Temp. room
Spearman's rho	Temp. Water	Correlation Coefficient	1.000	0.956**	0.812*	0.899*
		Sig. (2-tailed)	0.0	0.003	0.050	0.015
		N	6	6	6	6
	Temp. saturated soil	Correlation Coefficient	0.956**	1.000	0.812*	0.812*
		Sig. (2-tailed)	0.003	0.0	0.050	0.050
		N	6	6	6	6
	Temp. dry soil	Correlation Coefficient	0.812*	0.812*	1.000	0.657
		Sig. (2-tailed)	0.050	0.050	0.0	0.156
		N	6	6	6	6
	Temp. room	Correlation Coefficient	0.899*	0.812*	0.657	1.000
		Sig. (2-tailed)	0.015	0.050	0.156	0.0
		N	6	6	6	6

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

which simply revealed that the difference between the measurements of the four groups' core tendencies was not significant. In other words, while ambient temperature influences the stability of the capacitor oscillator circuit, the difference in measurements of the central trend of temperature from (a) water, (b) saturated soil, (c) dry soil, and (d) a room affects the stability of the oscillator capacitor circuit. There is no meaningful difference at the 95% confidence level. As a result, we must analyze the relationship between two variables, which can be characterized using a nonparametric analysis of variance and correlation. Table 2 shows how the so-called Spearman correlation coefficient is used to assess this performance. Tables 2 show the size and direction of the relationship between the temperature of water, saturated soil, dry soil, and a room.

Results from the Spearman correlation coefficient as presented in Table 2 showed the difference in the magnitude-changing trend of correlation coefficient between the temperature of water, saturated soil, dry soil, and a room. Table 2 lets us know that the magnitude-changing trend of correlation coefficient between the temperature of water and saturated soil as presented by the correlation coefficient is significant at the 0.01 level, equal to 0.956.

Furthermore, the correlation coefficient shows a significant magnitude-changing trend between the temperature of water and dry soil, water and room, saturated soil and dry soil, and saturated soil and room at the 0.05 level, with values of 0.812, 0.899, 0.812, and 0.812, respectively. The final pair depicts the magnitude-changing trend of correlation coefficient between the temperature of dry soil and a room, as represented by a correlation coefficient of 0.657, although not significant.

Part 2: Because water held in pores by surface tension is likely to contribute to the capacitance

probe's frequency response, which is primarily determined by the number of water molecules free to relax as their dipoles respond to field reversals (Dean *et al.*, 1987), it must be tested that the electric potential difference in frequency response of the capacitive probe from the three different water content test materials (A, B, and C) has different trends depending on the water content difference. Test the difference in electric potential between three test materials: (A) pure water; (B) soil saturated with water (silky); and (C) soil dehydrated by the weight or volume of water ejected during oven-drying at 105°C per unit weight or volume. This test is divided into two steps, as shown below.

Step 1: In this step, we used the nonparametric approach to a two-way ANOVA to compare raw data, which was divided into six groups (six replications) measured at least on an ordinal scale. It is so-called the Friedman Two-way Analysis of Variance by Ranks. Table 3 shows the raw data, which was separated into six groups (six replications) to test the capacitive probe's electric potential difference in frequency response every two minutes using three different water content test materials.

Table 3 revealed that there were three treatments (k) and six samples (N). Probabilities associated with values of chi-square rank calculation = 12.00 are equal to 0.00013 ($p = 0.00013$), which is in the 95% region for all six groups (or all six replications). According to the statistical test described in Siegel (1956) Table N, the probability (p) value is less than 0.05.

Findings from a two-way ANOVA were used to compare the six replications. Tell us that the probabilities associated with the values of the chi-square rank calculation of all groups are equal based on the six replications. In other words, there is a significant enough difference between the capacitive probe's electric potential difference in

Table 3. The raw data was separated into six groups (six replications) to test the capacitive probe's electric potential difference in frequency response every two minutes using three different water content test materials

(a) Measurement replication 1 st			(b) Measurement replication 2 nd		
Electric Potential (V)			Electric Potential (V)		
(A) Water	(B) Saturated soil	(C) Dry soil	(A) Water	(B) Saturated soil	(C) Dry soil
1.412	1.417	1.402	1.418	1.421	1.404
1.412	1.416	1.402	1.416	1.420	1.404
1.411	1.416	1.403	1.416	1.420	1.404
1.412	1.416	1.403	1.416	1.420	1.404
1.411	1.417	1.403	1.415	1.420	1.404
1.412	1.417	1.403	1.414	1.420	1.404

(c) Measurement replication 3 rd			(d) Measurement replication 4 th		
Electric Potential (V)			Electric Potential (V)		
(A) Water	(B) Saturated soil	(C) Dry soil	(A) Water	(B) Saturated soil	(C) Dry soil
1.416	1.420	1.404	1.417	1.420	1.404
1.415	1.420	1.404	1.416	1.420	1.404
1.415	1.420	1.404	1.416	1.420	1.404
1.415	1.419	1.404	1.414	1.420	1.404
1.414	1.420	1.404	1.414	1.420	1.404
1.414	1.419	1.404	1.415	1.420	1.404

(e) Measurement replication 5 th			(f) Measurement replication 6 th		
Electric Potential (V)			Electric Potential (V)		
(A) Water	(B) Saturated soil	(C) Dry soil	(A) Water	(B) Saturated soil	(C) Dry soil
1.416	1.420	1.404	1.416	1.421	1.404
1.416	1.420	1.404	1.417	1.420	1.404
1.416	1.420	1.404	1.417	1.421	1.404
1.416	1.420	1.404	1.416	1.421	1.404
1.416	1.420	1.404	1.416	1.421	1.404
1.415	1.420	1.404	1.416	1.420	1.404

frequency response every two minutes using three different water content test materials from all the groups to warrant statistical significance at the 95 percent confidence level.

Step 2: In this stage, we use the Friedman Two-way Analysis of Variance by Ranks. Table 4 the raw data was separated into three groups (all replications) and evaluated every two minutes for the capacitive probe's electric potential difference in frequency response using three different water content test materials.

Tables 3 and 4 show that this measurement does not calibrate with standard chemicals. Because it is calibrated using the principle of depicting a perfect direct link, one of the primary principles of study design is to maximize systematic or desirable variance, minimize error variance, and control the effect of extraneous variables. This principle was known as "MAXMINCON" by Kerlinger and Pedhazur (1973) and Kerlinger (1986).

They agreed that when both the dependent and independent variables are continuous, regression analysis should be employed to investigate the independent variable's contribution to the

prediction model. When an independent variable is continuously measured as advised by Nunnally (1978) using a validated instrument, the data produced closely approximates a true continuous measure and has the characteristics of a ratio-leveled measured variable (Kerlinger, 1986).

To test the capacitive probe's electric potential difference in frequency response every two minutes using three different methods, within-group variance was interpreted as the effect of extraneous variables such as soil cation exchange capacity (CEC), soil particles carrying net negative electrostatic charges, and soil's ability to hold positively charged ions. They are not included in the between-group variance as predictor variable coefficients due to the capacitive probe's electric potential difference in frequency response every two minutes. However, these factors are included in group variation, or "MAXMINCON" of the ANOVA technique.

Figure 4 depicts a nonparametric approach to a two-way ANOVA comparing three groups: (A) pure water; (B) soil saturated with water (silky); and (C) soil dehydrated by the weight or volume of

Table 4. The raw data was divided into three groups (all replications) and tested every two minutes for the capacitive probe's electric potential difference in frequency response with three distinct water content test materials

Measurement replication	Index	Electric Potential (V)		
		(A) Water	(B) Saturated soil	(C) Dry soil
1 st	1	1.412	1.417	1.402
	2	1.412	1.416	1.402
	3	1.411	1.416	1.403
	4	1.412	1.416	1.403
	5	1.411	1.417	1.403
	6	1.412	1.417	1.403
2 nd	1	1.418	1.421	1.404
	2	1.416	1.420	1.404
	3	1.416	1.420	1.404
	4	1.416	1.420	1.404
	5	1.415	1.420	1.404
	6	1.414	1.420	1.404
3 rd	1	1.416	1.420	1.404
	2	1.415	1.420	1.404
	3	1.415	1.420	1.404
	4	1.415	1.419	1.404
	5	1.414	1.420	1.404
	6	1.414	1.419	1.404
4 th	1	1.417	1.420	1.404
	2	1.416	1.420	1.404
	3	1.416	1.420	1.404
	4	1.414	1.420	1.404
	5	1.414	1.420	1.404
	6	1.415	1.420	1.404
5 th	1	1.416	1.420	1.404
	2	1.416	1.420	1.404
	3	1.416	1.420	1.404
	4	1.416	1.420	1.404
	5	1.416	1.420	1.404
	6	1.415	1.420	1.404
6 th	1	1.416	1.421	1.404
	2	1.417	1.420	1.404
	3	1.417	1.421	1.404
	4	1.416	1.421	1.404
	5	1.416	1.421	1.404
	6	1.416	1.420	1.404

water ejected during oven-drying at 105°C per unit weight or volume. The test statistic chi-square calculation equals 72.00, and the chi-square critical equals 5.994, which is within the 95 percent confidence level of null hypotheses and so rejected.

Findings from a two-way ANOVA used to compare three groups (all replications) tell us that the difference between the mean ranks of the comparison three groups from all replications (the big group) is big enough to be statistically significant at the 95 percent confidence level. In other words, the capacitive probe's electric potential difference in frequency response every two minutes using three different water content test materials from *all* replications (the big group) is statistically significant at the 95% confidence level.

Part 3: Because theoretical considerations suggest that the probe may respond to only part of

the total water content of the soil, presumably that which is least strongly held by surface absorption forces and surface tension, there may be no direct general relationship between the electricity variable and water content (Bell *et al.*, 1987). As a result, we must construct a linear relationship between the voltage electricity variable and water content using the statistical technique of linear regression, as indicated by the standard gravimetric method. The statistical technique of linear regression, as indicated by the standard gravimetric method of the study area, as follows in Figure.5.

Part 4: Because soil water content (SWC) indicates the quantity of water in the soil but not its availability to plants (Irmak *et al.*, 2001), we must understand the relative availability of the amount of water held in the soil profile for plant uptake or use, known as soil matric potential (SMP). SMP reveals

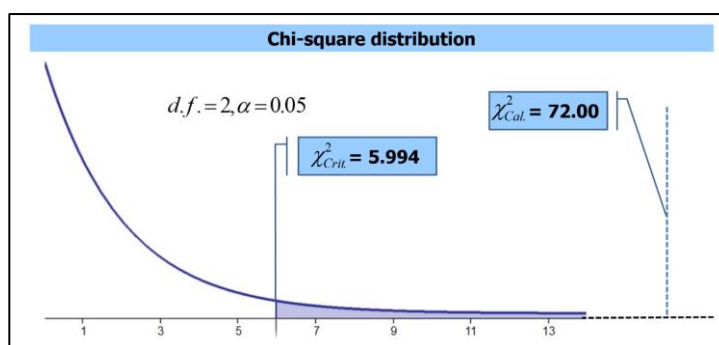


Figure 4. Nonparametric approach to the two-way ANOVA to test the difference in electric potential between the three test materials in all replications

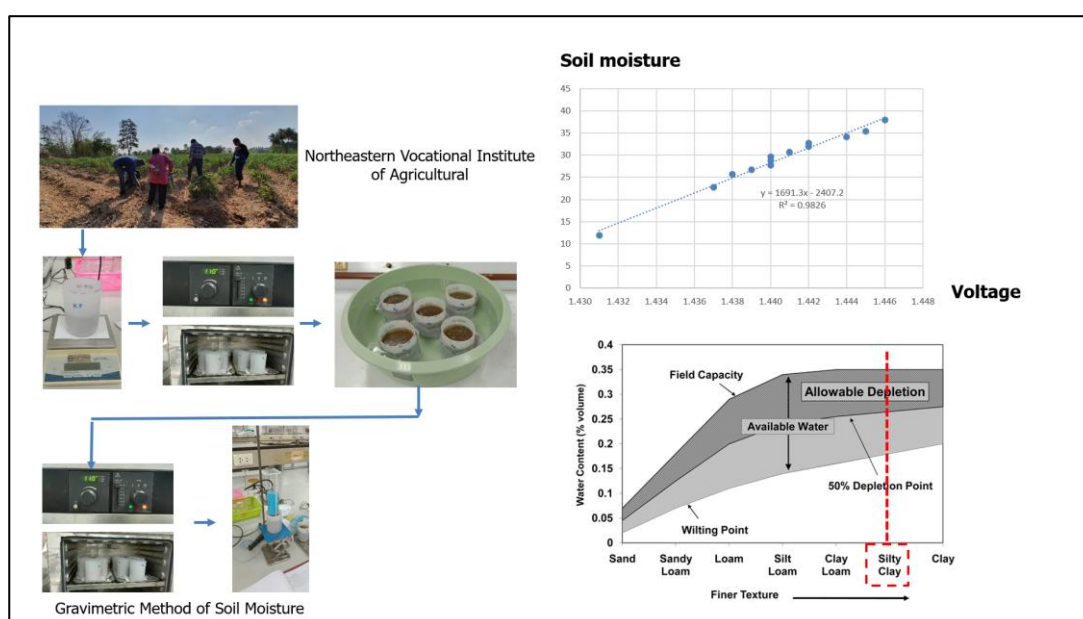


Figure 5. The statistical technique of linear regression, as indicated by the standard gravimetric method of the study area

how much energy plants will use to extract water molecules from soil particles. If the soil moisture sensors are not properly calibrated, the trigger points and soil moisture sensor readings will be incorrect, resulting in suboptimal crop production, a waste of energy, time, labor, water, and financial resources, and a compromise in yield quality and quantity. The relationship between SWC and SMP as indicated by the standard gravimetric method of the study area, as follows in Figure 6.

Conclusions

Gravimetric calibration was performed on the complete sensor system. The original difference

between the two measurements was related to a difference in the density of the soil used in laboratory studies, which was corrected when the density was equalized. The effect of ambient temperature on soil moisture measurement was investigated both experimentally and computationally; however, the difference in mean rankings across all groups was not statistically significant. We also integrated the sensor with a custom-built electronic board array for deployment in the field. A simple soil moisture sensor was created using the capacitance between two parallel rods, which can be measured using calibrated stainless steel tubes.

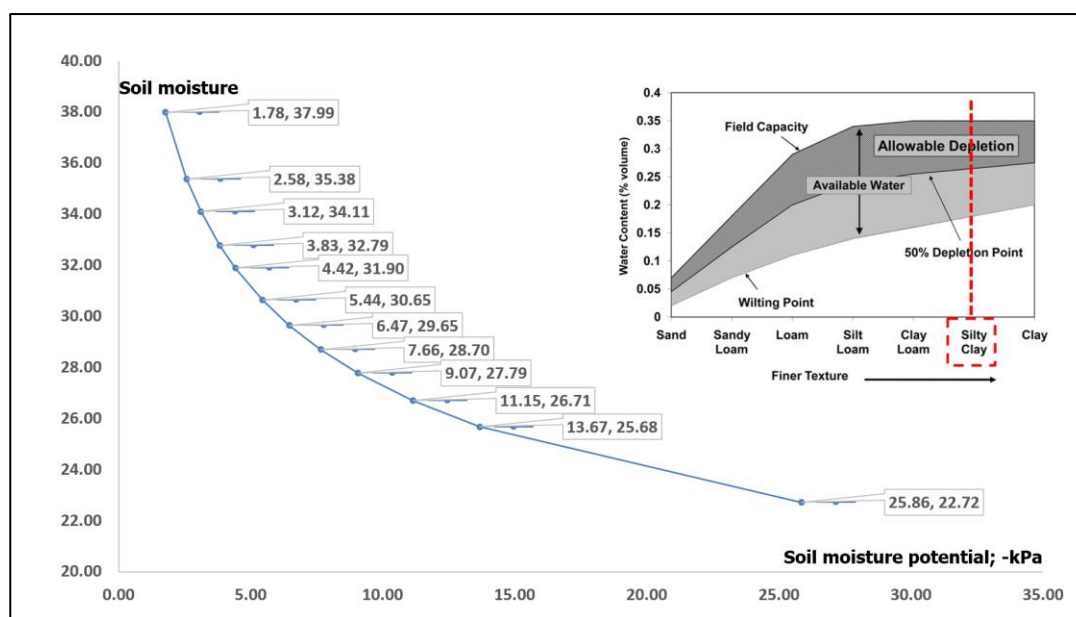


Figure 6. The relationship between SWC and SMP as indicated by the standard gravimetric method of the study area

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