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MEASUREMENT PRECISION AND ACCURACY OF SELECTED SOIL MOISTURE SENSORS IN RESPONSE TO CHANGING TYPE AND CONTENT OF SOIL ORGANIC MATTER

Diploma Thesis

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Declaration

This is to declare that this MSc. Thesis with the title "measurement precision, comparability and calibration of selected soil moisture sensors" is an original work by me and all sources quoted are cited and respective authors are acknowledged in the references. I certify that I author this and did not copy directly from a third party

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Abstract

Various soil moisture sensors are widely used for research and practical purposes. However their accuracy and precision can be affected either the sensors themselves, either by various soil conditions in which they are used. This study was conducted to 1) carry out the individual sensor calibration for comparison of selected soil moisture sensors in order to evaluate the sensor precision and various reading devices response; 2) evaluate the sensor accuracy affected by different amount and type of organic matter added to the soil. Sensors 5TE and EC-5 combined with ProCheck, EM50 datalogger and ECHOcheck reading devices were tested. Two organic matter sources; biochar and compost were applied to soil of original organic carbon content of 2.07% from Český Krumlov district in the South Bohemia region of the Czech Republic at two organic carbon levels of 4% and 8%. Soil was artificially repacked into containers for uniform distribution considering the average dry bulk density of the soil originally determined in the field and measurements were taken after that using the various sensors and reading devices followed by gravimetric method of water content determination. This was repeated for series of moisture levels of 0% to 30% in intervals of 5% for each organic matter treatment where these organic materials were thoroughly mixed with the soil at ratios to obtain the desired organic matter level. Statistics showed significant differences among the individual sensors on one hand, and strong correlations between various organic matter levels and sensor outputs on the other hand, with accuracy of factory calibrations ranging between 3.1% and 7.1% which was improved by own calibration between 0.5 and 1% revealing the effects of changing types of organic matter content on the measurement precision and accuracy of soil moisture sensors.

Keywords: soil water content, 5TE, factory calibration, soil organic matter

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1. Introduction

Soil water content is fundamental for geo-ecological research and related fields since it is a key state variable in the soil (Rosenbaum *et al.*, 2010) and its measurement is very important in science as well as in practice. For example, it helps farmers to plan irrigation periods. Soil water content monitoring is inconceivable without indirect measuring methods, presented in variety of soil water content sensors with various possibilities to use, different prices and also different accuracy and precision. A perfect sensor would exactly measure the same value for various repeated measurements or estimations (Matula *et al.*, 2016).

Manufacturers of soil water content sensors supply their products with output registering volumetric soil water content (θ). It is, however, important to know where this number comes from and what it means. Likely, the output value from the sensor will not be exactly equal to the actual θ of the soil we are working on. For this reason, there is the need to calibrate these sensors (Parvin and Degré, 2016) as recommended by the manufacturers for specific soils in the case of significant difference from what they offer as their factory calibration to be able to be sure of the values from the reading we achieve and to investigate other possible sources of error in the sensor measurements. Some sources of error in soil water content measurement include ability of the sensor to measure dielectric permittivity, temperature, installation quality, soil bulk density and different soil texture, dielectric properties of soils regarding their mineralogical and chemical compound, and different quality of calibration supplied by the manufacturer (Bissey, 2009). In addition, sensor to sensor variation and different response to various reading devices can be observed.

Some sources of error can be reduced when measurement is carried out in laboratory on homogenized soil samples, thus the differences in results are likely to arise from the sensors themselves and the reading devices. In addition, organic carbon content effect on the sensors' performance has been little investigated as mentioned by Fares *et al.* (2016a). Biochar and compost representing stable and easily decomposable organic matter, respectively, which effect bulk density and water retention capacity of soils with their different physical characteristics comparing to mineral particles were chosen to observe their role in effecting sensor readings with respect to the actual water content in the soil.

2. Scientific Hypothesis and Objectives

2.1 Scientific Hypothesis

Based on the findings in literature, the following hypotheses were formulated:

1) Sensor precision (sensor-to-sensor readings) may significantly affect the results of measuring network. In addition, different response of sensors is obtained via various reading devices.
2) Sensor measuring accuracy (resulting water content) is affected by the amount and type of soil organic matter content.

2.2 Objectives

Following the hypotheses, the main objectives of the thesis are:

1) To carry out the individual sensor calibration for comparison of selected soil moisture sensors under controlled laboratory conditions in order to evaluate the sensor precision and various reading devices response in sandy loam cambisol from Malonty locality in South Bohemia.
2) To evaluate the sensor accuracy affected by different amount and type of organic matter added to the soil. Two types of organic matter will be used, easily decomposable compost material and stable commercially available biochar (Agro-Protect-Soil).

3. Literature Review

3.1 Soil water content

Water in soil is a fundamental connection in the hydrological cycle that controls exchange with the environment above and with the groundwater beneath. It has crucial effect on many of the physical, chemical, and biological procedures that take place in soils. Water in soil acts both as a lubricant and as a coupling agent among the soil particulate materials, along these lines impacting the structural stability and quality of soil and geologic materials (Topp and Ferre, 2002). According to Mittelbach et al. (2012) and Parvin and Degré, (2016), "the moisture dynamics of soil affects water fluxes throughout the soil profile, evapotranspiration and surface erosion". It is a key variable controlling the trading of vitality and water transitions between the land surface and climate. Because of its high connections with air, it has a noteworthy effect on the improvement of climate designs including heat waves and precipitation (Kapilaratne and Lu, 2017). Water content in the soil, θ has been expressed as the ratio of the mass of water present in the sample before drying to the mass of the sample after it has been dried to a constant mass at 105°C (Reeb and Milota, 1999; Romano, 2014). On another hand soil water is termed as water regardless of the phase present in the soil profile (in vadose zone) and is a state variable controlling a wide exhibit of ecological, hydrological, geotechnical, and meteorological processes (Seneviratne et al., 2010).

Since water is one of the main restraining factors in agricultural processes, it is crucial to quantify its availability in effective root zone and identify modern ways to regulating both productive such as transpiration and non-productive such as evaporation, leakage and runoff fluxes of water. In addition, soil water balance is necessary as it forms a useful framework to study the effect of agricultural innovations. It links sequential changes in the amount of water available in the soil (w), with water added to the soil by precipitation (P) and irrigation (Q_I), and water losses from the soil through evaporation and transpiration combined as evapotranspiration (ET), leakage (L) which is percolation beyond the root zone and runoff (Q_R). The relationship between these sequential changes over a period, (t) is represented in the equation below:

$$d_w / d_t = P + Q_I - ET - L - Q_R \qquad \text{Eq. (1)}$$

The soil water balance equation is very important as it helps us to understand how plants utilize and interrupt with water available to them (Fischer et al., 2019). A long-term study of soil water content for an area will give an idea on the best use of the soil in the land area. Constant observation of soil water content in the vadose zone was expressed by Fares et al. (2016b) as a basic for ideal water system planning just as for some other hydrologic applications, for example, allocation of water and calculation of groundwater recharge. Furthermore, it expresses that soil water content is additionally a central point that decides plant development and solute transport in irrigated and non-irrigated regions. The regulation of soil water content during exchanges of water and heat at the land surface plays a significant role in the development of weather and climate. Thus, the Global Climate Observing System initiative has recognized soil water content as an essential climate variable (Benninga et al., 2018) Wendroth et al. (2008) formed a useful conceptual framework for demonstrating the importance of soil water on soil physical properties affecting plant growth which is illustrated in Figure 1a. This shows that a decreasing water content in the soil increases the mechanical resistance which makes it harder for plant roots to penetrate the soil, but on the other hand increases the temperature and aeration. However, an increasing water content causes the reverse. Water, therefore, is the major control on physical properties of soil which affects plant growth. It also said to exert a strong control on soil biogeochemistry which includes microbial activity, mineralization of nitrogen and biogeochemical cycling of nitrogen and carbon as illustrated in Figure 1b below:

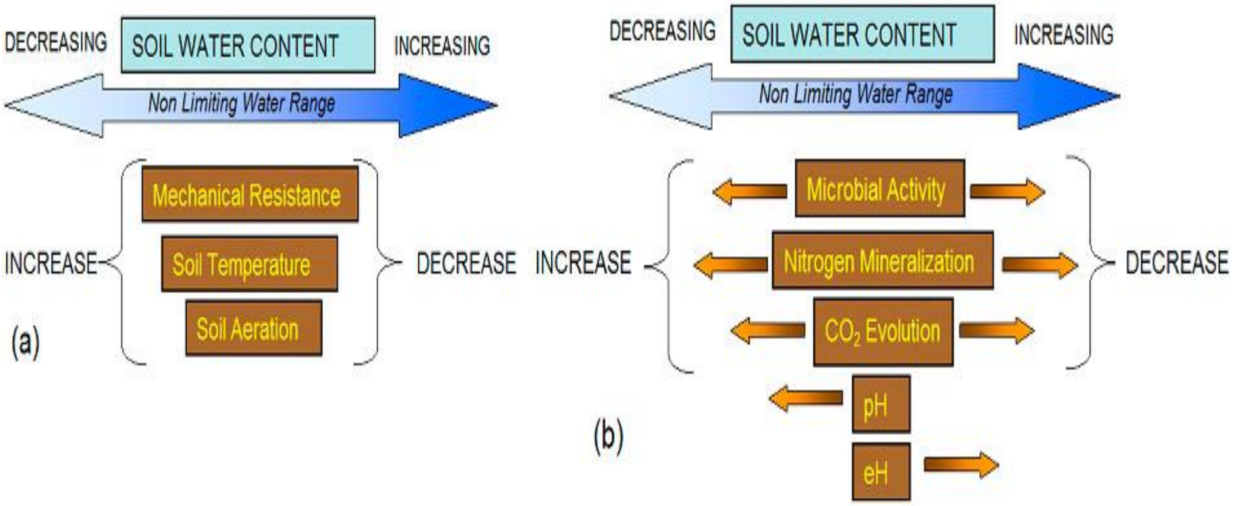

Figure 1. (a) Soil physical properties under changing water content conditions; (b) Soil biogeochemical properties under different water content conditions (Wendroth et al., 2008).

Soil water content on another hand also affects many hydrological and ecological processes that are important for a wide range of applications from the regional to local scales. Regional water management can benefit from sensible and reliable statistics about soil water content which can improve quantifications of risks by flood and its effect on rainfall assessments and streamflow forecasts and negative irregularities to current plant water demands are an indicator of droughts. The agricultural sector relies on enough root zone soil water accessibility for crop growth, while excess of soil water channels to severe losses. Moreover, conditions of wet soil are unfavorable for farmlands and these can endanger the timely implementation of essential agricultural practices and cause physical damage to the land. Soil water content is relevant to evaluate the effects of groundwater removals, drainage systems and irrigation systems (Benninga et al., 2018).

Soil water content measurements are valuable and very salient for understanding soil water dynamics in the vadose zone for upscaling and linking in situ soil water measurements with remotely sensed imagery and for providing measurements for the standardization and validation of hydrology and biophysical models according to Gasch et al. (2017a). The success of soil water content estimation from earth observations depends on the specifications of the sensor, the assumptions and parameter values implemented for the retrieval algorithms, and the soil and vegetation cover conditions (Harm-Jan et al., 2018). Water content measurement is a major interest when evaluating water regime in soils (Kodešová et al., 2011). Precise and persistent estimations of temperature, apparent electrical conductivity (EC), apparent dielectric permittivity (ε_a), and volumetric water content (Θ_v) are very important to irrigation management and other agronomic choices (Singh et al., 2018)**.** Conditions of soil water content can be quantified using in situ devices, earth observations and land process models subject to atmospheric forcing terms (Harm-Jan et al., 2018).

3.2 Soil water content measuring techniques

There are different methods used in determination of soil water content. Some of these were mentioned by Schmugge et al. (1980). **Gravimetric technique** is standard for calibration of all other soil moisture determination techniques. In this method, the soil sample is oven dried to a temperature of 105°C until a constant weight is obtained (Hillel, 1998). The accessible soil water content estimation techniques are named immediate or circuitous or in simple terms; direct or indirect (Fares et al., 2016b). Gravimetric method is however, the only direct method and the most accurate method for quantifying soil moisture. But since it is destructive and involves high labour, it is not suitable for continuous monitoring, thus different types of techniques have been invented to estimate soil moisture in response to these shortcomings, over the years of which the most commonly used are electromagnetic sensors (Parvin and Degré, 2016). These sensors are used widely for determining the soil water content of a given location continuously (Gabriel et al., 2010). All other methods than gravimetric fall in the classification of indirect methods as the water content of porous media is calculated indirectly from other measurable variables (for example electrical resistance or relative permittivity) depending on the water content (Báťková et al., 2013). Aside from remote sensing, the other techniques utilized for soil water content measurement are ground-based, where the sensors are set in direct contact with the soil or the land area to be monitored (Fares et al., 2016b). Some of these methods are described in the following chapter.

3.2.1 Indirect methods of soil water content determination

Neutron scattering technique estimates the water content of the soil by measuring the thermalized or slow neutron density. The density of the resulting cloud of slow neutrons is said to be a function of the soil water content in the liquid, solid, or vapor state. The number of slow neutrons returning to the detector per unit time is counted, and the soil water content is determined however from a calibration curve previously determined by number of counts versus volumetric water content (Hillel, 1998).

Electromagnetic techniques. There is developing enthusiasm for the utilization of sensor systems to address the "perfect time" measurement of accuracy of farming parameters both through business applications and research on enhanced water-use management. Dependable and thorough checking of soil water content over the landscapes is irreplaceable for application of some water resources. In situ soil water content estimating using gadgets with capacitance are broadly utilized in spite of their effects to soil properties other than water content (Scudiero et al., 2012; Fares et al., 2016a). One of the advantages shown by researches is these electromagnetic sensors are cost-effective and can produce a large quantity of measurements that can capture the total pattern of soil moisture in a given soil profile (Parvin and Degré, 2016). The electromagnetic techniques depend upon the effect of water content on the electrical properties of soil. It was stated that the magnetic permeability of soils is very close to that of free space hence the electromagnetic approaches exploit the moisture dependence of the soil's dielectric properties. Dielectric properties of moist soil may be characterized by a frequency-dependent complex dielectric response function (Oates et al., 2017; Schmugge et al., 1980).

Electromagnetic sensors are utilized to build up nonstop in situ soil moisture systems. These sensors make utilization of the high relative permittivity of water to estimate the volumetric water content in the soil (Hanson and Peters, 2000; Mittelbach et al., 2012; Parvin and Degré, 2016). Determination of soil relative permittivity is applied in different soil water sensing probes like **Time Domain Reflectometry** (TDR) and **Frequency Domain Reflectometry** (FDR) (Matula et al., 2016). The TDR sensors, however, are the costliest yet the most precise under field conditions because of their lower sensitivity for soil properties and temperature variations. Calibration relationships of TDR are very steady or stable to variations in soil type, and well-known general calibration relationships exist, despite the fact that calibration relationships for soils with extensive mud or organic matter content can vary essentially from these general connections (Western and Seyfried, 2005). In this way, TDR sensors are regularly utilized as reference sensors in moisture monitoring networks (for example Oz Net in Australia). Interestingly, non-TDR sensors are frequently criticized because of their high sensitivity to soil properties and temperature and FDR sensors for their high-temperature sensitivity. In spite of the fact that they are less accurate, non-TDR sensors are widely utilized in soil moisture networks for long-term monitoring because they are low in terms of price, easy to use and low power utilization (Kapilaratne and Lu, 2017). Frequency Domain Reflectometry test is utilized to measure the water content of soils. This principle is based on the fact that relative permittivity among water and air contrasts by a factor of 80. Subsequently, the availability of water in the soil between the probes of the sensors produces a very critical change in its capacitance, the higher the concentration of water, the higher the capacitance which can then be estimated by electrical methods. Since the probe is insulated there is no immediate flow stream inside the soil, thus the conductive impact of ion-based salts in the soil is limited. However, different types of soil are expected to show diverse properties and these properties are prone to effect sensor readings (Oates et al., 2017).

All sensor information or data are downloaded and documented as volumetric water content (Θ_{sensor}) which is automatically converted from apparent dielectric permittivity (ε_a)

utilizing a factory calibration equation. Every model of a sensor has a factory calibration equation that is unique for them.

3.3 Soil Moisture Sensor systems, precision and their calibration process

3.3.1 Soil Moisture sensor systems

Soil water content sensor systems can enhance our comprehension of vadose zone processes at the catchment or field-scale. Two-and three-dimensional powerful soil water information can be utilized for consolidation into an approval of hydrologic and biophysical models. Sensors that record transiently thick or dense soil, crop or barometrical estimations can be joined with spatial information to create or develop spatiotemporal models. For agricultural sensor networks, the most regularly estimated parameter is soil water content (Gasch et al., 2017). A **soil moisture sensor** is a device that measures the quantity of water contained in the soil thus volumetric water content (θ) of soil (Shakoor, 2016).

Mathematically θ, is given as follows;

$$\theta = A_s W \qquad \text{Eq. (2)}$$

$$W = [(W_w - W_d) / W_d] \qquad \text{Eq. (3)}$$

Where,

θ is water content by volume (cm^3/cm^3)
A_s is dry bulk density (g/ cm^3)
W is water content by mass (g/g)
W_w is mass of wet soil (g)
W_d mass of dry soil (g) (Shakoor, 2016).

To obtain an accurate measurement, Spelman et al. (2013) confirmed that soil-specific calibration or adjustments of soil water sensors are required for better accuracy. When expressing the performance of soil moisture sensors, precision and accuracy are observed. Their exact meaning related to sensors is explained as follows.

3.3.2 Precision and Accuracy

Accuracy suggests how close the measured value is to the actual value or the maximum difference that will exist between the measured value and the actual value determined by a standard reference procedure. **Precision** can also be termed as the degree of reproducibility of said measurement. Precision on the other hand is characterized as the capacity of estimation to be reliably or consistently repeated. A perfect sensor would exactly measure the same value for various repeated measurements or estimations (Bissey, 2009; Matula et al., 2016). Though these measurements are said to be repeated consistently it is however stated by Fares et al. (2016a) that sensor precision does not generally ensure accuracy. It continues to say that sensor perusing could be exact and yet wrong when sensor readings go erroneously from the real qualities.

Several studies (e.g. Fares et al., 2007; Vaz et al., 2013) suggested that despite the fact that the use of soil water content monitoring sensors is now increasing in modern days, the accuracy and precision of these sensors are affected by soil physical properties, such as bulk density, porosity, and temperature. Moreover sensor’s ability to measure apparent dielectric permittivity accurately, relationship between apparent dielectric permittivity and volumetric water content, installation quality are also factors affecting the accuracy of these sensors (Bissey, 2009). Mittelbach et al. (2012) also stated some chemical properties such as electrical conductivity and salinity plays different roles in affecting its accuracy and precision.

3.3.3 Calibration Process

In recent decades, extensive advancement has been made in soil moisture sensor technology to automatically measure soil moisture in situ dependent on electromagnetic methods. These sensors are easy to utilize and install; their estimations are in real life and simultaneous over the scene (Fares et al., 2016b). Sensors, for example, the Decagon10HS and 5TE sensors are however two broadly known sensors of the capacitance type which come with empirical manufacturer equations to estimate from relative permittivity (ε_a), which are respected substantial for a wide scope of soils (Visconti et al., 2014). A calibration equation is however created and used to measure the soil water content depending on the sensors' reaction to the dielectric permittivity of the soil–moisture–air blend. However dry plant tissue makes it necessary to calibrate these sensors for a particular soil to improve the performance of the sensors (Fares et al., 2016b). In addition, calibrations are generally provided by manufacturers, regularly including both raw signals to soil moisture just as apparent dielectric permittivity to soil moisture connections. Even though these sensors are calibrated and validated over a wide scope of soil types, there is general agreement that these capacities of calibrations cannot apply to or hold for all soil conditions, so soil-and site-explicit calibrations are regularly required to enhance the measurement precision. While a lot of authors find manufacturers' default calibrations sufficiently accurate for various mineral soil types (apart from very clayey soils), many studies conclude that calibrations specific to organic-rich soils and humus horizons are vital (Bircher et al., 2016). There are different types of sensors developed using capacitance and impedance as well as time- or frequency-domain reflectometry and transmissometry methods. The shape and design of the sensors as well as the measurement and/or interpretation of raw data is highly variable (Robinson et al., 2008). "Nevertheless, they all take advantage of the large difference between the relative permittivity relative to free space of dry soil and water in order to estimate the volumetric fraction of the latter'' (Simone et al., 2016).

To calibrate means to check or adjust by comparison with a standard. As mentioned earlier, these sensors since they measure and record different output values of θ of the soil we are working on and for that matter there is the need to check and adjust the sensors so that they can measure accurately with less window of error. There is usually factory calibration available yet calibration is needed especially when they are to be used in volcanic soils, soils with high electrical conductivity levels, peat soil, different medium other than soil and if the sensors are to be used in a manner they are not designed for (Bissey, 2009; Rosenbaum et al., 2010). The factory calibration is in a variety of soil types and materials of varying apparent dielectric permittivity. Specific soil conditions however at the point of insertion can influence the variability of the sensors (Rosenbaum et al., 2010). Because of variations in soil bulk density, mineralogy, texture and salinity, the generic mineral calibration for current ECH_2O sensors (EC-5, 10HS, 5TE, 5TM) results in approximately ± 3 to 4% accuracy for most mineral soils and approximately ± 5% for soilless growth substrates such as potting soil and rock wool. Accuracy, however, increases to ± 1 to 2% for all soils and soilless substrates with soil specific calibration. Decagon Devices Inc.

recommended that ECH_2O sensor users conduct a soil-specific calibration for the best possible accuracy in volumetric water content measurements (Cobos, 2009).

Some custom calibration methods were listed by Bissey (2009) as (1) Dry down method, (2) Hanging water column in non-soil water media and (3) Homogenized soil calibration.

1) For the dry down method, sensors are placed in saturated soil in a large container (with or without plants) and the container is weighed to calculate actual volumetric water content. The actual volumetric water content is correlated with sensor output. This method appears to imitate environmental conditions and disturbance of soil is minimized. Results from this method depends highly on the position of the sensor in the container and moreover it is not a widely accepted method for sensor calibration.

2) The hanging water column method on the other hand utilizes soils of very low bulk density and high organic matter content where changes in the water column brings change in the water content in the soil and finally, wet soil in the column is completely dried to calculate absolute water content. It is a quick method and bulk density generally remain consistent during the calibration process. It is expensive as it requires costly instrument and operation is moderately difficult.

3) The last one being the homogenized soil method used in this experiment is widely used and this method was further employed in this thesis. It involves the use of a transparent calibrating container with an appropriate size and shape to accommodate the sensor's zone of influence. The soil sample is collected at preferred depth, dry bulk density calculated, then soil is air dried with large particles removed. Having done that, soil is packed into the calibrating container in different replicates with different moisture levels and the sensors inserted, readings taken with desired and compatible reading devices and undisturbed samples taken for actual volumetric water content. Calibration is then carried out by plotting the output raw data against actual volumetric water content calculated to find the linear regression (or other

relationship) using the method of least squares. This is one of the widely used methods of approximation which thus;

$$f(x) \equiv \mathrm{y} = \mathrm{ax} + \mathrm{b} \qquad \text{Eq. (4)}$$

Where;
- y is the dependent variable (soil water content in this case)
- x is the independent variable (raw sensor output in this case)
- a is the slope of the fitted line
- b is the intercept and expresses the value of y for the case, when $x = 0$

Calibrations in the laboratory on individual sensors prior to installation may not represent the specific soil conditions as in the field, and this approach is said to be unrealistic for many sensors in a heterogeneous setting (Gasch et al., 2017a).

3.4 Soil organic matter and organic carbon

The main component of soil organic matter (SOM) which consisting of plant residues and animal manure is organic carbon (C) which is generally about 40 to 60 % and other elements such as oxygen (O), 35 to 40 %, hydrogen (H) and nitrogen (N) representing 4 to 6 % each and sulphur (S), 1 %. In the process of SOM decomposition, these elements are released mostly in their gaseous states, which represents an important source of greenhouse gases such as CO_2, CH_4, N_2O) emission (Ondrasek et al., 2019). The SOM which is mainly the form of carbon content in the soils is due to the decomposition of the organic residues by microorganisms.

Organic matter has an overwhelming effect on most of the soil properties, even though it is generally present in relatively small amounts. A soil that is typical for agricultural soil has 1% to 6% of organic matter. It comprises of three particularly extraordinary parts thus living beings, new deposits, and all-around deteriorated buildups (Fred and Harold, 2009). Moreover, it differs from mineral by its complex structures and small bulk densities. High porosities as results and large specific surface areas caused by the presence of organic matter increases substantial water holding capacities up to 0.8 to 0.9 cm^3/cm^3 compared to around 0.4 to 0.6 cm^3/cm^3 in the case of mineral soils (Simone et al., 2016). While the impacts of most soil properties on the performance of sensors are all around archived and well documented, there is lack of studies on the impact of SOM on the performance of soil water content monitoring sensors. Understanding the impact of SOM on soil moisture sensor readings will assist the endeavors with developing viable ways to deal with up/down-scale moisture readings at various spatial and fleeting scales. One of the studies dealing with this issues was carried out by Fares et al. (2016a) and they made it clear that, continued to state that organic matter had a significant effect on the sensor readings. It was found out from the same study that there is a strong negative correlation between the organic matter level and sensor readings; sensor readings decreased with increasing organic matter content. The figure below shows the findings between organic matter level and sensor readings.

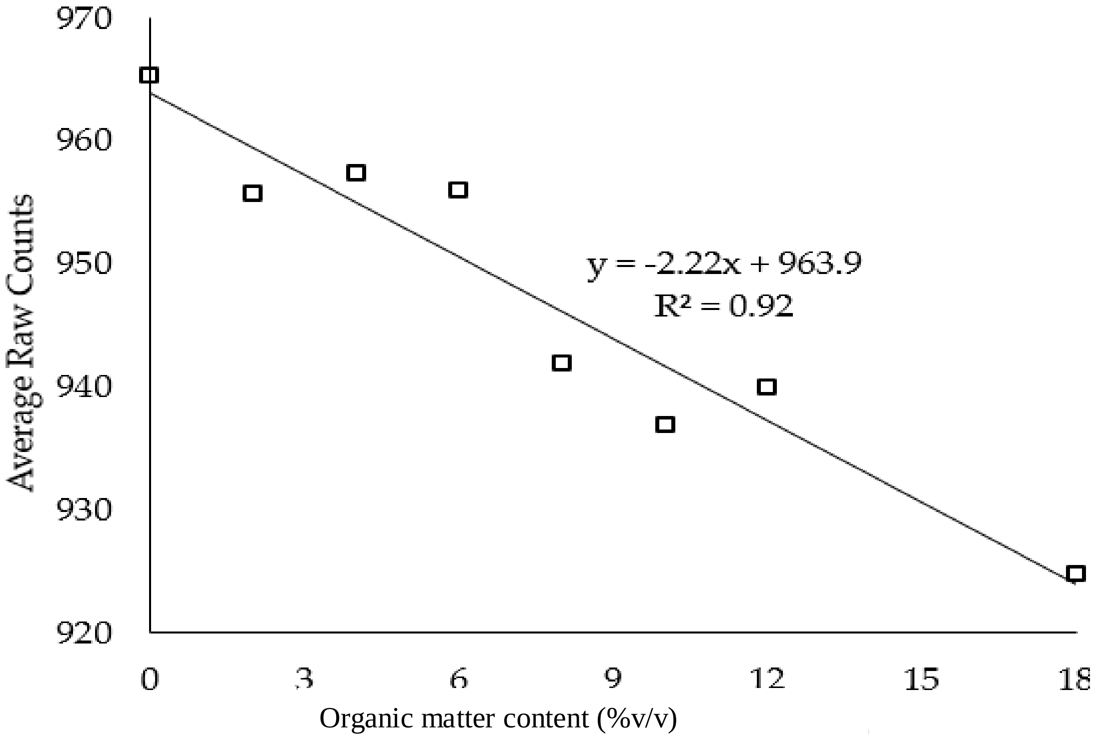

Figure 2. Correlation between organic matter level and average sensor readings (Fares et al., 2016a).

The accuracy and precision of the sensors used based on the findings on Figure 6 above can be seen to be significantly affected by the organic matter level.

3.4.1 Different types of Soil Organic Matter, Sources and their Stability

SOM composition and categorization is widely elaborated in many studies and emphasis is mostly laid on non-living SOM rather than soil living biotas which includes microbes, plants roots and fauna. Non-living SOM comprises of two main types thus; (1) relatively stable, complex, humified material that dominates (>90 %) and (2) unstable (easily decomposable) organics (for example compost) (Ondrasek et al., 2019).

Another type of stable SOM is obtained by biomass carbonisation. “Biochar is a carbon-rich byproduct of bioenergy production produced by slow pyrolysis or gasification’’ (Smith and Trippe, 2019). It is a material rich in organic carbon and has proven its potential in the enhancement of soil quality by practical applications, carbon sequester, and moderate the procedure of an Earth-wide temperature boost simply known as global warming. Like the way charcoal is created from wood, the production of biochar is powered by various feedstocks, organic agricultural wastes; for example, grasses, leftover harvest stalks, biomass, and so on. Laboratory and some field studies have shown that biochar stabilizes and controls soil water nutrients and salinity. It also supports root growth and is advantageous for soil microbial communities and promotes carbon sequestration in the soil. Some positive effects of biochar are on bulk density, pH, cation exchange capacity and soil organic carbon (Fischer et al., 2019).

Biochar can be applied as a treatment on the soil surface or mixed into the soil. Application of biochar on the soil surface has only a slight effect on the soil physical properties (Blanco-Canqui, 2017). However, mixing biochar into deeper soil layers modifies soil physical properties such as particle size, shape and texture depending on the type of biochar material (Lim and Spokas, 2018). The reason is biochar interrupts the soil environment by changing the pore size distribution. In fine textured loam and clay soils, biochar helps in the formation of large pores (Sun and Lu, 2014), while it decreases the pore spaces in sandy soils with course texture (Liu et al., 2017). Biochar additions decrease soil bulk density (Sun and Lu, 2014), and for that matter, porosity is as well affected. This decrease is as a result of higher interpore volumes (Liu et al., 2017), aggregate stability, and binding of particles which is attained under biochar additions.

These effects on the soil matrix change proportionality with increasing amounts of biochar (Blanco-Canqui, 2017).

Changes brought by biochar on the physical properties of soil affect its hydraulic properties. Application of biochar on the soil surface forms a layer that can temporarily reduce the infiltration capacity and hydraulic conductivity at the soil surface owing to the hydrophobic properties of biochar (Fischer et al., 2019). Mixing biochar into deeper soil layers have influence on its matric potential. Thus modifies the soil water retention curve (SWRC) (Sun and Lu, 2014). The SWRC is a relationship between volumetric soil water content and soil matric potential, and this varies in relation to soil texture and particle size distribution. (Fischer et al., 2019). The modification of the SWRC affects the binding of water to the soil, soil water content since these two are relative to the SWRC. Availability of water as well is affected. Biochar particles create larger interpore space in soils with fine texture in that way enhancing water flow and availability in the unsaturated zone (Sun and Lu, 2014). In coarse textured soils on the other hand, biochar hinders the larger soil pores, thus impeding the flow of water and improving water retention (Liu et al., 2017).

Studies by Fischer et al. (2019) shows that biochar modified soils tend to show an increased soil water content with respect to control treatments It was observed that adding biochar to the soil in an idealized (but realistic) scenario shifts the water retention curves towards more positive water potential values at a given volumetric soil moisture level as can be seen on Figure 3 below. Soil moisture dry-down for both the control and biochar amended soils against time from their findings as shown in Figure 4. These shows higher water retention capacity of soils treated with biochar and these can be future studied to quantify the effects of biochar addition to soil over longer periods.

Compost on the other hand is considerably, an environmentally safe, agronomically advantageous, and a relatively cheap organic amendment which stimulates microbial activity in the soil and crop growth (Ros et al., 2006). Similar to biochar, compost improves soil fertility, carbon sequestration potential, biological and physical properties leading to desertification control, aids in soil respiration and metabolic activity in the soil (Albaladejo et al., 2009)

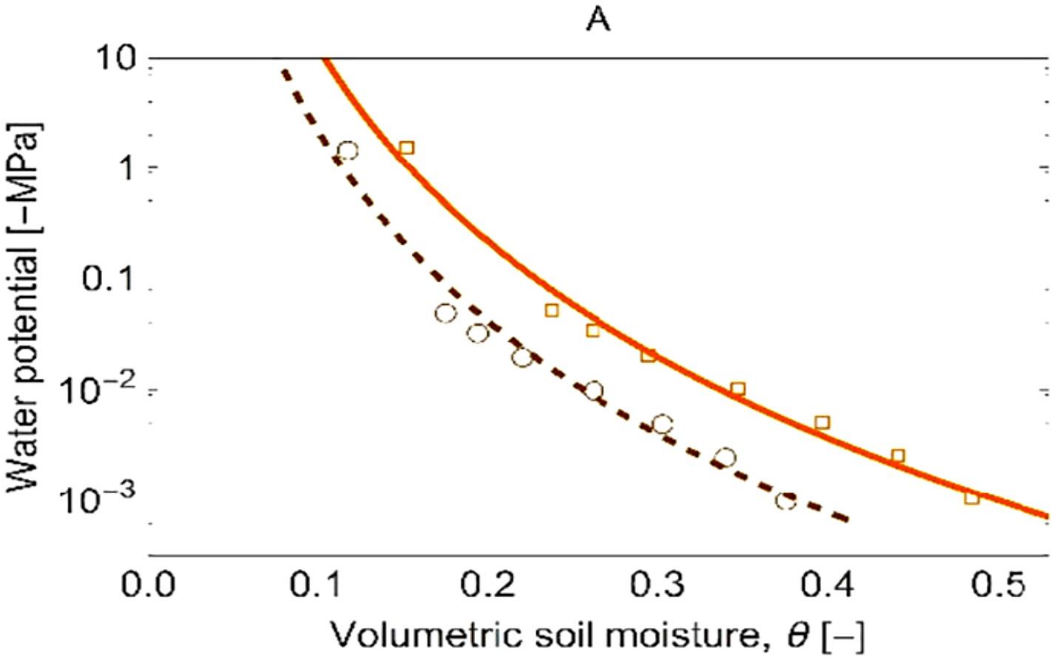

Figure 3 Soil water retention curves linking soil water potential (ψ) to relative volumetric soil moisture (θ) for soils treated with biochar (indicated by red line) and control soils (indicated by black dashes) (Fischer et al., 2019)

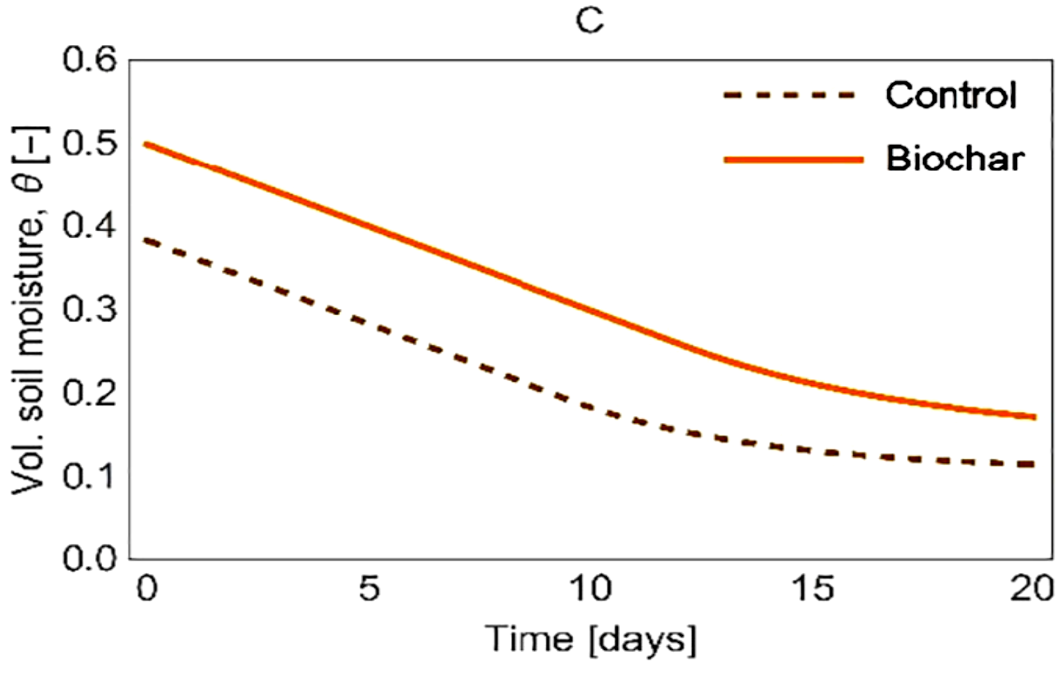

Figure 4 Temporal evolution of soil saturation water moisture during an extended dry period for the two soils; the initial condition is set to the field capacity and water losses from the soil are modelled using the evapotranspiration-saturation relations (Fischer et al., 2019)

4. Materials and Methods

4.1 Materials

4.1.1 Soil

The soil used in this study was Cambisol of sandy loam texture collected from the surface horizon (0-15 cm) from the field in Malonty locality in spring 2018. The field is located at 48°42’21.9’’N and 14°34’46.0’’E, district Český Krumlov, region South Bohemia, and belongs to Bemagro a.s. company (Figure 9). The soil has an average Ph value of 5.5, electrical conductivity of 221 µS/cm, organic carbon content of 2.07% in its dry matter, average field dry bulk density around 1.38 g/cm^3, particle density of 2.61 g/cm^3 and total porosity around 47 %.

The soil after collection was air-dried, crashed and sieved on 2 mm sieve. All the soil material was thoroughly mixed to achieve maximum homogeneity.

Two variants of ECH_2O sensors; EC-5 and 5TE were evaluated and measuring devices such as EM50 data logger, ECH_2O CHECK reading device, ProCheck data logger and ECHCO Utility software all by the Meter group were utilized in this experiment.

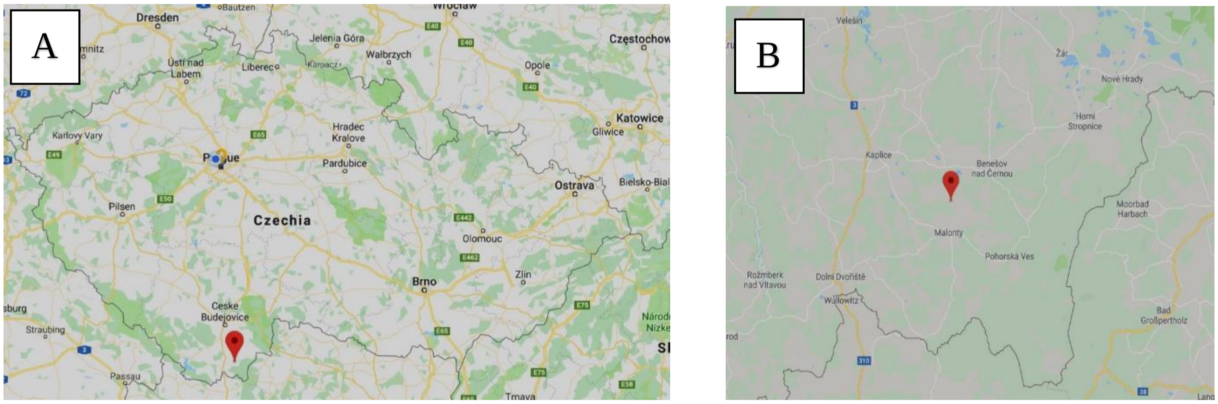

Figure 5. (A) Google map pin of the sampling area in the Czech Republic and (B) showing the close view on the locality.

4.1.2 Soil organic matter admixtures

Two types of soil organic matter were mixed into the soil:

(a) Compost, representing an easily decomposable organic matter, which was farm-made compost from Bemagro company with an addition of commercially available plant growing substrate. Since they are two different compost, they were mixed homogeneously by adding 40 % of the farm-made vermicompost and 60 % of commercially available plant growing substrate. These two were mixed thoroughly to achieve homogeneity. The commercial substrate was added due to improving structure and workability of the final organic material.

(b) Biochar, representing a stable soil organic matter, which was a commercially available product called Agro-Protect-Soil from Ekogrill s.r.o. company.

4.1.3 Soil moisture sensors and reading devices

SENSORS

(a) 5TE Soil Moisture, Temperature, and Electrical Conductivity Sensor

The 5TE sensor (METER Group Inc.) uses an electromagnetic field to measure the dielectric permittivity of the surrounding medium, then determines soil water content (θ) by measuring the relative permittivity of the media using capacitance or frequency domain technology. The sensor supplies a 70 MHz oscillating wave to the sensor prong that charges according to the dielectric of the material. The stored charge is proportional to soil dielectric and θ. The 5TE microprocessor measures the charge and outputs a value of dielectric permittivity from the sensors. It is one of the widely known sensors of the capacitance type (Varble and Chávez, 2011). Some advantages are it records 3 measurements in one (thus, volumetric water content, electrical conductivity and temperature), has plug and play capability and has salt monitoring capabilities. Its dimensions are 10.9 × 3.4 × 1.0 cm and the prong length is 5.0 cm (see Figure 2). When calibrating using reading devices such as Meter ProCheck reader, DataTrac 3, or ECH2O Utility in a mineral soil requires the use of the Topp equation below to convert raw dielectric values (METER Group, 2019a).

$$\theta = 4.3 \times 10^{-6}\, \varepsilon^3_a - 5.5 \times 10^{-4}\, \varepsilon^2_a + 2.92 \times 10^{-2}\, \varepsilon_a - 5.3\ 10^{-2} \qquad \text{Eq. (5)}$$

Where,

θ is volumetric water content (cm^3/cm^3)

ε_a is apparent dielectric permittivity (unitless).

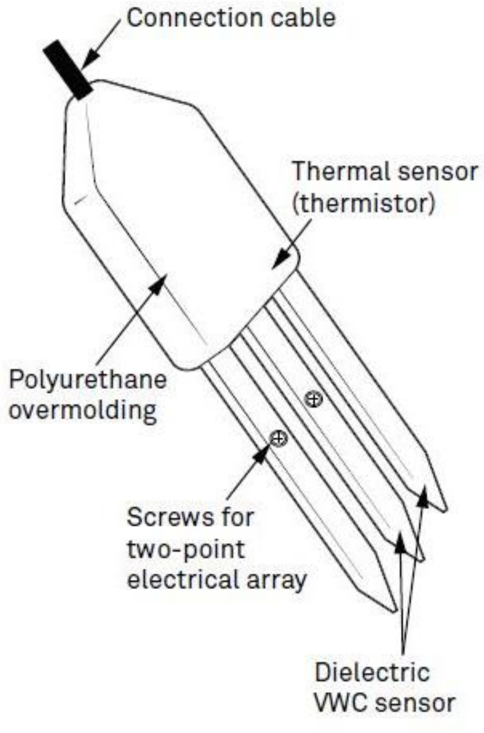

Figure 6: Scheme of 5TE moisture sensor (METER Group, 2019a).

(b) ECH$_2$O EC-5 moisture sensor

The EC-5 sensor (METER Group Inc.) determines volumetric water content by measuring the relative permittivity of the media using capacitance or frequency domain technology. It has an approximate volume measurement range of 0.2 L. Moreover, it is handy and easy to install in the field and can also be used in nursery pots and the lab. The EC-5's compact design with sharp edges makes it easy to push directly into undisturbed soil to ensure accuracy and it also supplies a 70 MHz oscillating wave to the sensor prong that charges according to the dielectric of the material just like the 5TE (see Figure 7).

Its dimensions are 8.9 × 1.8 × 0.7 cm and the prong length is 5.0 cm. When calibrating using a METER software or the user calibration menu in the ProCheck is used the RAW calibration is said to be used. According to METER tests, a single calibration equation generally suffices for all mineral soil types with electrical conductivities from 0.1 to 10 dS/m saturation extract. The θ is given by equations below (Meter Group, 2019b).

$$\theta = (8.5 \times 10^{-4})\,(RAW) - 0.48 \qquad \text{Eq. (6)}$$

where RAW (mV) is the output from the METER data logger using 3-V excitation.
If a non-METER data logger is being used, VWC is given by

$$\theta = (11.9 \times 10^{-4})\,(mV) - 0.401 \qquad \text{Eq. (7)}$$

In experiment, ECH_2O Check was used record the θ values for the ECH_2O EC-5 moisture sensor so the equation (4) was used to convert raw data in mV to θ since the ECH_2O Check is no more considered a device by the METER GROUP.

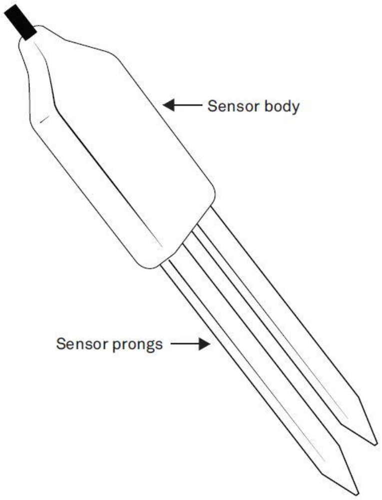

Figure 7: Scheme of ECH_2O EC-5 (Meter Group, 2019b).

READING DEVICES

(a) ECH$_2$O CHECK Reading device

The ECH2O Check is a hand-held readout device designed for use with Decagon's ECH2O soil moisture sensors. It was discontinued by the meter group since they merged and for that matter, the ECH$_2$O Check is still treated as a Decagon device. It does not store any data so is simply used for making a quick measurement. It has a simple two-button interface to initiate readings, scroll through different unit options, and adjust calibration. It can display its data in terms of three different units: percentage volumetric water content, PCT; inches per foot, IPF; and Analog to Digital Converter, ADC number counts. The ECH2O Check has different calibration settings for each type of ECH2O sensor. (Meter Group, 2019c).

Figure 8: ECH$_2$O CHECK Reading device (Meter Group, 2019c).

(b) ProCheck Sensor Read-Out and Storage System

The ProCheck (Figure 9) is a handheld readout device for use with all soil moisture sensors and environmental monitoring sensors made or sold by Decagon Devices Inc. (now METER Group Inc.) and is low cost, easy to use, versatile handheld meter for the water content sensors. It can be used to spot-check soil volumetric water content, temperature and/or salinity in the field, laboratory, glasshouse or greenhouse. It is ideal for checking the water content of pots or shallow soils. It is also ideal for students and teaching.

The sensors are easily connected into the top of the ProCheck with a stereo plug. Values from the sensors are displayed on the LCD screen. These data can be stored inside of the ProCheck for later download into an Excel file. The ProCheck can store up to 5,000 readings. Each reading includes sensor type, date, time, raw value, calibrated value, and calibration coefficients. Some sensors supported by the ProCheck are; EC-5 Soil Moisture, 5TE Moisture, Temp & EC, EC-10 Soil Moisture, 10HS Soil Moisture, 5TM Moisture & Temp and few more (Meter Group, 2019d).

Figure 9: Procheck Sensor Read-Out and Storage System (Meter Group, 2019d).

(c) Em50 Digital Data Logger and ECH2O Utility software

The Em50 belongs to the Em50® series of data loggers comprising of; Em50, Em50R and Em50G by the METER Group Inc. The Em50 is manual and the rest two are remote controlled. It has 5 sensor ports and one communication port which is used to connect it to the computer for data downloading. Rather than having a screen and a keyboard, the Em50 is configured by plugging a laptop into the comm port which makes communication with the ECH2O Utility software provides setup windows which name the logger, set the logger clock, select the type of sensor on each port, and specify how often you want the sensors to read. The Em50 can store more than 36,000 data scans. A scan includes the logger name, date, time, and measurements from each of the five ports. The Em50 Data logger is only compatible with sensors made by METER. The ECH2O Utility software which provides a simple way to connect to and configure the data loggers makes downloading and processing of data fast and easy (Meter Group, 2019e).

4.2 Experimental Setup.

Firstly, basic soil properties such as dry bulk density and organic carbon content of the soil, biochar, and compost were determined.

Measurement of water content was performed by utilizing two variants of ECH_2O soil moisture sensors (5TE Moisture Sensor and ECH_2O EC-5 moisture sensor in 5 and 3 replicates respectively) combined with reading devices such as ECH_2O CHECK, ProCheck, Em50 Data Logger connected to ECH2O Utility software (all devices manufactured by METER Group) in scheduled order for each target soil water content.

Measurement by the sensors was carried out in containers with uniformly repacked soil; the measurements were repeated for seven prepared target soil water contents. Several undisturbed soil samples were taken from each container and actual volumetric water content and dry bulk density were determined by gravimetric method. This experimental setup was repeated for soil with 5 levels of organic matter content, such as original amount (pure soil), two levels of compost (representing easily decomposable organic matter), and two levels of biochar (representing stable organic matter). The levels were selected as 4 and 8 %.

A scheme of effective sensors measurements and control sampling was suggested before the start of the whole experiment considering the size of the calibration container, sampling rings and the sensors as can be found on Figures 10 and 11:

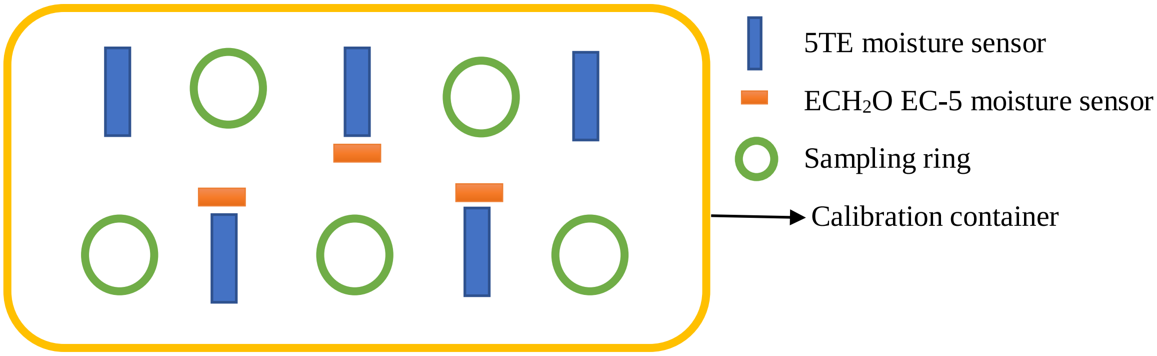

Figure 10. Experimental scheme for sensor measurements and sampling.

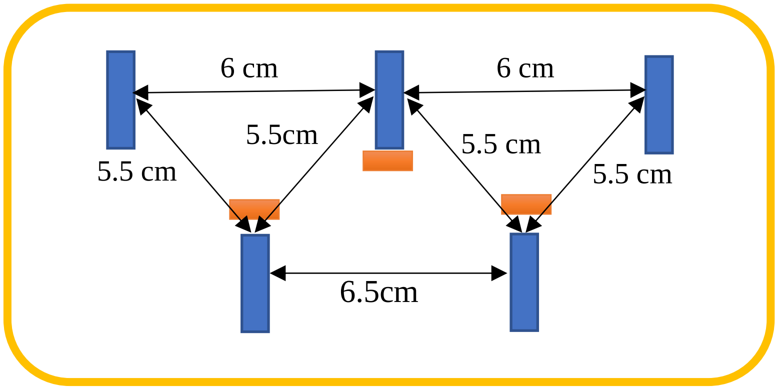

Figure 11: Scheme of distance between sensors.

4.2.1 Determination of particle density, bulk density, and porosity

Core ring (100 cm^3) was used to determine the field dry bulk density (see e.g. Hillel, 1998), which was then considered for repacking the soil into the container. The water pycnometer method (according to standard procedure CEN ISO/TS 17892-3) was employed to determine the particle density of the soil sample. Total porosity was calculated using the two densities.

4.2.2 Organic carbon content determination of the soil sample, compost, and biochar.

The content of organic carbon in the soil sample, compost and biochar were necessary to determine as it gives an idea of the amount of the organic carbon needed to be able to quantify the effects on the precision of soil moisture sensors and soil water content.

A modified Walkley-Black method (Page et al., 1982) by rapid dichromate oxidation was used. Soils were oxidized with 2 N $K_2Cr_2O_7$ and H_2SO_4, and back titrated with 0.1 N $K_2Cr_2O_7$ to determine organic carbon content. The amount of $K_2Cr_2O_7$ used was recorded in all cases and calculations were made to determine the percentage of organic carbon in the dry matter of the soil sample, compost and biochar. These values were needed for determination of the mass of biochar and compost to be added separately (mixing ration) to the soil sample to get the desired percentage of target organic content at each target bulk density for the mixtures. Some pictures of these process can be found in Appendices 5 and 6.

Amount of organic carbon was determined as follows: soil 2.07 %, compost 22.8 % and biochar 47.1 %.

4.2.3 Soil sample preparation for calibration

The soil was carefully prepared by first air drying and plant roots, gravel and other foreign materials were removed before sieving through a 2-mm sieve to create a homogeneous soil condition to allow for optimal contact between the soil and the sensors. This was followed by homogeneously mixing with distilled water to attain the desired moisture level after which it was repacked using a plastic tamper to compact the soil paying special attention to precise work into the transparent 5 l calibration container with dimensions 28 × 19 × 14 cm in which layers of one liter have been marked in order to achieve uniform packing of the soil and uniform target water content. Packing was done with respect to target bulk densities thus, 1.38, 1.34 and 1.30 g/cm^3 for each or each organic carbon content level of 2%, 4% and 8% respectively. The dry bulk density was decreased proportionally to the increasing amount of SOM.

1) Packing of raw soil sample at each stage was done considering desired bulk densities and organic matter content as mentioned above. Precautions were taken to make sure the repacking was done in layers to keep the homogeneity and uniformity of the prepared sample in terms of dry bulk density and a transparent container was chosen to ensure that the compressing of soil is uniformly done across the whole container before the next layer (see Figure 12). The mass of soil considered for a target bulk density with its corresponding organic matter content was repeated for each layer with desired moisture levels 0% ,5%, 10%, 15%, 20%, 25%, and 30% throughout the whole experiment. When considering moisture levels other than 0%, a distilled water was used as a neutral medium to prevent extra ions from making way into the mixture hence increasing conductivity which may influence sensor readings. The order of the procedures was kept consistently the same during all replicates in order to reduce the effect of evaporation from the repacked soil columns. Moisture level 0% means air dry soil. The same soil was used during all experiment, air-dried between each repetition.

2) In the case of changing the percentage of desired organic carbon content level such as of 4% and 8%, the soil was homogeneously mixed with biochar or compost at their respective stages with a dry mass ratio in order to obtain these organic carbon content desired. After the soil is artificially packed for each moisture level, the next stage was to insert the sensors for measurement.

Figure 12: *Calibration container with its layers and how the repaking was done in layers.*

4.2.4 Soil water content measurements

Before the start of this stage, the various sensors were labeled so as not to mix them to observe the sensor to sensor variability as well. Precautions were taken by cleaning the sensor probes with distilled water and drying after every step. The steps were as follows:

1) The entire probes of the sensors were carefully pushed into the packed soil at desired positions as indicated on the scheme on Figure 11 after each moisture level at reasonable intervals and readings were taken. The intervals were chosen based on the sensing region of the sensors to avoid interference. Precautions were taken by pushing the sensors in a straight line and not shaking them so as not to introduce any air gaps between the sensor probes and the soil and there was a proper spacing between the sensors to avoid any interference between them. Five different 5TE moisture sensors labeled 1 to 5, and three different ECH_2O EC-5 moisture sensors labeled and used alternatively for the various moisture levels were utilized and readings were timed to ensure consistency.

    (a) The 5TE sensors were first one by one connected to a ProCheck reading device which was set to record data for 5TE sensor and readings were recorded making sure the reading on the sensor is stable for at least 5 to 8 seconds.

    (b) These 5TE sensors are then connected to all the 5 sensor ports of Em50 Data Logger powered by five AA batteries and connected to ECH2O Utility software on the computer which was set to record data at intervals of 1-minute and monitored for 5 minutes to record consistent data. The datalogger temporarily store a sensor reading each second and the second value that is recorded is the mean of 60 readings stored within one minute and data is then downloaded to an Excel file with proper file naming.

2) After finishing with 5TE, the ECH_2O EC-5 sensors were also carefully inserted into the soil in positions as can be seen in the scheme presented on Figure 11 and then connected one after the other to the ECH_2O CHECK with readings recorded in millivolts (mV).

4.2.5 Sampling for volumetric water content determination

Having recorded data from the sensors, undisturbed samples were taken between the measuring spots without removing the sensors (so as not to disturb the soil) using small Kopecky's rings with volume of 15.7 cm^3. It must be noted that the dimensions provided by the manufacturer for the rings were found to be incorrect, so a correct measurement was done to calculate the correct volume of the rings. Undisturbed samples were carefully taken, then placed on a watch glass which was initially weighed, and the mass was of wet sample was recorded immediately to ensure that no water is lost by evaporation. Timing was kept consistently the same for all replicates. Samples were then placed into oven with a temperature of 105^oC and real volumetric water content and bulk density were determined by the gravimetric method. This was repeated for all organic carbon content levels and their corresponding moisture levels.

4.3 Statistical analysis

In order to test the measurement precision and accuracy of the water content measured by several sensors and registered by several reading devices in their response to different organic matter type and variety, a one-way analysis of variance (ANOVA); Duncan's Test with $p < 0.05$ was performed using Statistica 13 software package to test the statistical differences.

Root-mean-square deviation (RMSD) was calculated to test the differences between the values determined using the gravimetric method and the values obtained from the sensor reading hence the accuracy of the sensors by their factory calibrations was quantified. The correlation coefficient (r) was employed to estimate the statistical relationship to indicate the strength of the relationship between the gravimetric determined soil water content with the sensor output values.

Moreover, the Mean Absolute Error (MAE) between measured water contents and gravimetric water contents were also calculated to test the accuracy of the default calibration of the sensors in estimating actual water content.

These statistical indicators are in details described in Wösten et al. (2001).

5. Results

All laboratory data from the data loggers and reading devices were gathered for each moisture level and organized in Excel tables, either raw data, either θ provided by factory calibration were stored. The results were then screened for blatant sensor errors (in this case, the volumetric water content of one of the 5TE sensors labeled number 5 connected to Procheck recorded a negative value for 8% organic carbon content using compost with 0% moisture level).

In Table 1 is summary of all measurements done. In total, 35 repacked containers were prepared and measured with 8 pieces of sensors by 3 reading devices, and 5 undisturbed soil samples were taken from each container.

Table 1. Summary of the calibration measurements. Asterisks show linkage between sensor type and used reading devices.

Soil water content level (% vol.)	Organic matter content level	Sensor types	Reading devices
0 5 10 15 20 25 30	2.07% Natural soil (K) 4% Biochar added (B4) 8% Biochar added (B8) 4% Compost added (C4) 8% Compost added (C8)	5TE (5 pc) * EC5 (3 pc) ** Soil samples (5 pc) ***	ProCheck* EM50 data logger* ECH2O Check** Gravimetric method***

The raw values recorded by the ECH2O Check reading device was converted to volumetric water content using the sensor calibration equation (Eq. 7 in chapter 4.1.3). Results from the EM50 data logger were averaged.

5.1Precision of gravimetric soil water content

Data obtained by sensors were compared with the real volumetric water content determined by undisturbed soil samples. Therefore, the precision of the sampling is presented in Table 2. Average values from 5 samples from each container are presented for each treatment and moisture level as well as their coefficients of variation (CV, calculated as ratio of standard deviation and arithmetic mean). Variation is very low, which shows careful packing and thus the average values are representative to use in comparison with sensor outputs. Higher variation was obtained for 0% moisture level, because soil was in powdery state and thus mass water content was determined on disturbed sample, dry bulk density was estimated from dry mass of soil and volume of the container and θ then calculated by Eq. 2. Thus, the values may not illustrate the real conditions.

Table 2. Precision of the sampling and values determined by the gravimetric method (VWC is vol. water content in cm3/cm3, BD is dry bulk density in g/cm3, CV is coefficient of variation).

Target VWC (%)		0	5	10	15	20	25	30
K	VWC	0.018	0.052	0.097	0.147	0.194	0.250	0.309
	CV	8.8	2.9	1.6	0.7	1.7	1.0	1.4
	BD	1.36	1.34	1.16	1.26	1.28	1.31	1.42
	CV	na	2.5	4.6	0.9	1.6	1.7	0.8
B4	VWC	0.022	0.056	0.106	0.140	0.192	0.250	0.306
	CV	9.8	1.1	1.8	2.1	1.7	2.9	1.2
	BD	1.32	1.26	1.25	1.27	1.23	1.25	1.33
	CV	na	1.4	1.5	1.7	1.3	2.1	1.3
C4	VWC	0.023	0.068	0.107	0.141	0.208	0.247	0.306
	CV	7.2	1.2	4.0	6.3	2.0	3.0	0.8
	BD	1.32	1.28	1.25	1.25	1.19	1.24	1.33
	CV	na	1.6	1.4	2.8	1.5	2.9	2.8
B8	VWC	0.025	0.059	0.095	0.132	0.186	0.272	0.286
	CV	1.9	1.5	5.4	1.0	0.9	1.6	1.8
	BD	1.27	1.12	1.04	1.04	1.09	1.15	1.17
	CV	na	1.8	2.8	2.0	1.9	1.3	1.8
C8	VWC	0.024	0.062	0.097	0.135	0.176	0.240	0.300
	CV	2.4	1.7	1.0	2.1	1.4	2.3	1.2
	BD	1.28	1.08	1.02	1.03	0.98	1.04	1.05
	CV	na	2.0	2.4	2.8	1.3	2.0	1.9

Bulk density being one vital properties of soil was observed at each round of the experiment to examine its relationship with increasing water content. It was however observed that the bulk density decreased with increasing water content until around between 10% to 20% moisture levels that there was an increase with increasing moisture level in all organic carbon levels (see Table 2).

The decrease could be due to the dry nature of the samples at those moisture levels especially from 0% up to 15% making them a bit difficult to compress evenly to the desired bulk density which creates an error until it was near saturation. Also, in the case of 4% and 8% organic carbon level, of both biochar and compost, the increase in the volume of the soil as a result of the addition to obtain the said organic carbon content may also have contributed to the fall in bulk density from the beginning until the soil was getting more saturated.

5.2 Differences between individual sensors

Individually, the average reading of the sensors for both biochar and compost treatments seem to be behind the desired moisture levels except for 0% where no water was added but values were greater than zero. This is possible because the soil was just air dry. A close look at figure 13 and 14 reveals 5TE sensors measuring higher sensor measured water content in biochar treated soils than in compost treated soils in almost all cases. The same can be observed on figure 15 for ECH2O Check calculated volumetric water content for EC-5 sensors. This has already been established earlier as per the absorption abilities of the materials.

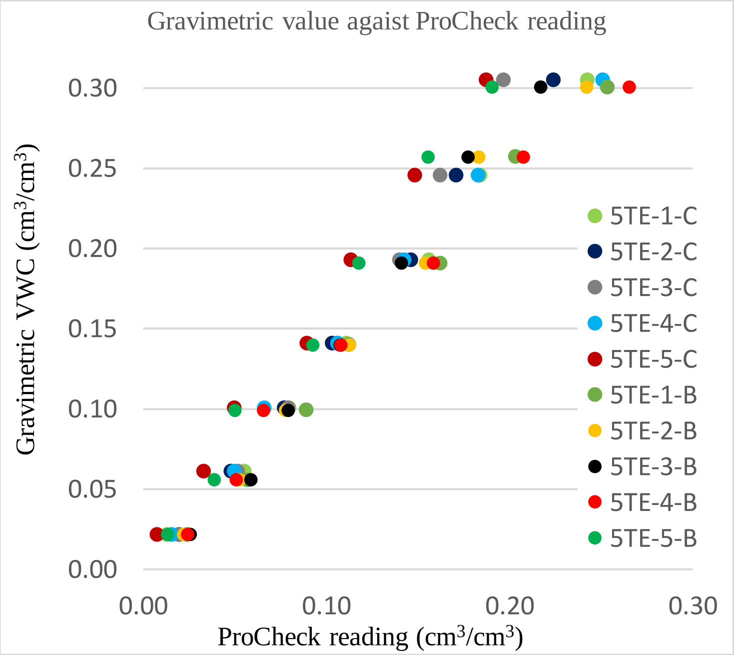

Figure 13: Comparison of average ProCheck reading for 5TE sensors with real volumetric water content obtained by gravimetric method for various moisture levels of Compost and Biochar mixed soil.

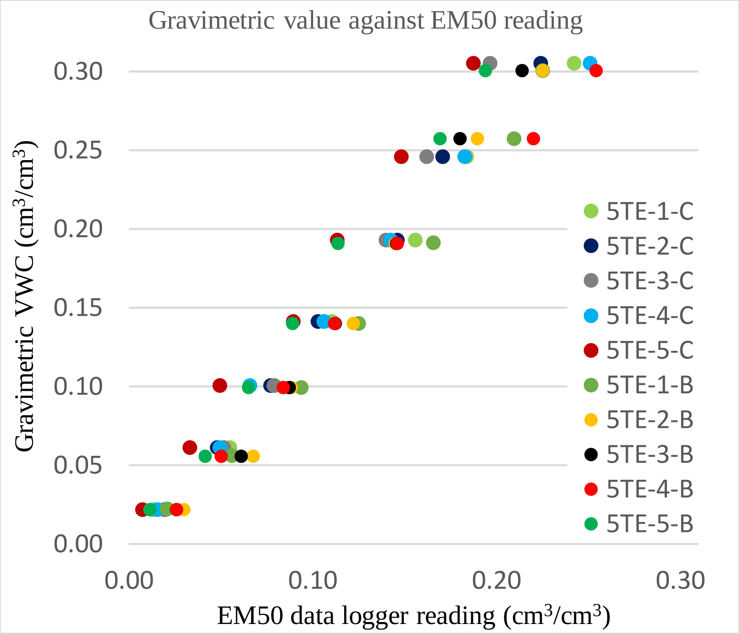

Figure 14: Comparison of average EM50 data logger reading for 5TE sensors with real volumetric water content obtained by gravimetric method for various moisture levels of Compost and Biochar mixed soil

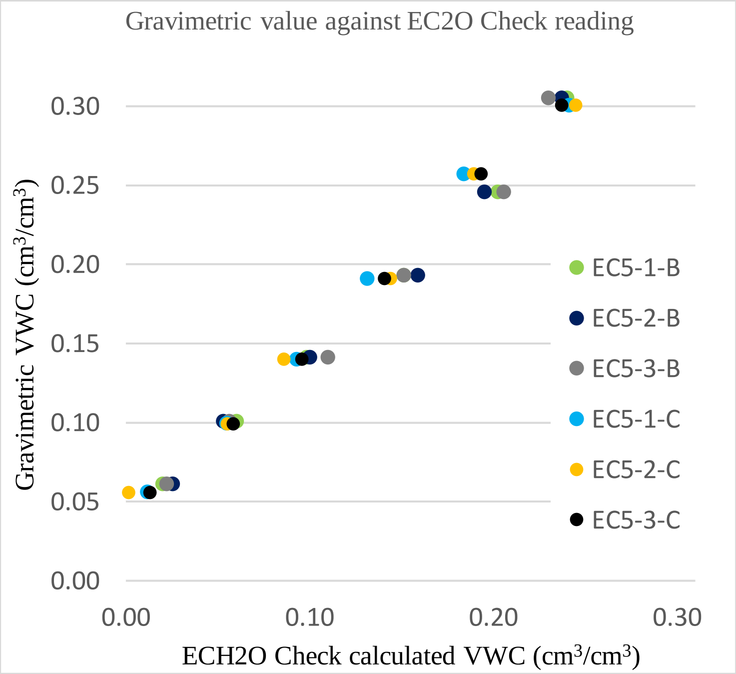

Figure 15: Comparison of average ECH2O CHECK reading for EC-5 sensors with real volumetric water content obtained by gravimetric method for various moisture levels of Compost and Biochar mixed soil

Table 3 shows 5TE sensor number 1 in most cases measured the highest mV value followed by sensor number 3. Sensor 1 has a significant similarity with all other sensor at 0% moisture level. Sensors 2. 3 and 4 has a significant similarity at 10%, 15% and 20% moisture levels and sensor 5 in all cases measured the least mV values and in almost all cases except for 0% moisture content has a statistically significant difference with all other sensors though there is a positive correlation between all the sensors with the gravimetric determined water content as can be seen in tables 3 and 4 below for all organic matter treatments. The case of the sensor number 5 is salient to say that there are possibilities of failures that can be expected from band new sensors since all the sensor used are band new.

Standard deviation calculated for the individual sensors can be observed to be increasing with increasing moisture levels from 15% to 30% in almost all cases but has some inconsistency in the case of 0% to 10% moisture levels.

Table 3: ANOVA comparing the significant statistical difference between average raw count volumetric water content recorded for each 5TE sensor by EM50 data logger and ProCheck.

EM50 + ProCheck	**0 % VWC**	**5 % VWC**	**10 % VWC**	**15 % VWC**	**20 % VWC**	**25 % VWC**	**30 % VWC**
Sensor Number	mV						
1	133.4 ab	201.4 ab	266.8 a	331.2 a	424.3 a	519.5 a	639.4 a
Min-Max	119-168	173-221	235-295	279-387	384-467	461-606	563-701
SD	14.77	14.22	16.54	31.91	30.55	50.91	47.76
2	144.3 a	207.8 a	243.5 b	318.9 ab	387.9 b	469.0 b	588.4 b
Min-Max	123-184	166-241	152-272	283-262	364-410	413-533	501-654
SD	17.54	22.06	34.4	28.07	17.35	42.83	52.24
3	145.9 a	209.2 a	254.7 ab	307.4 b	382.0 b	452.6 bc	541.4 bc
Min-Max	107-191	190-233	240-273	287-348	351-416	415-517	449-582
SD	22.93	16.09	12.45	17.04	20.2	34.94	40.52
4	141.2 a	189.9 b	237.0 b	307.1 b	389.6 b	519.2 a	675.5 a
Min-Max	118-185	163-212	208-264	287-344	319-472	375-645	554-764
SD	20.74	16.52	17.06	16.09	47.53	81.42	74.45
5	116.8 b	166.1 c	207.2 c	266.6 c	324.4 c	419.9 c	498.1 c
Min-Max	97-151	129-198	160-227	237-294	280-359	373-465	441-565
SD	16.37	19.16	19.38	18.55	28.62	31.69	38.75

ECH2O Check sensors provided similar results for every moisture level as can be seen in table 4 below. Analysis of average sensor reading values, however, did not show any significant differences among the sensors.

Table 4. ANOVA comparing the significant statistical difference between average raw count volumetric water content recorded for each EC-5 sensor by ECH2O Check

ECH20 Check	**0 % VWC**	**5 % VWC**	**10 % VWC**	**15 % VWC**	**20 % VWC**	**25 % VWC**	**30 % VWC**
Sensor Number	mV						
1	307.2	350.8	385.2	417.0	458.4	499.8	540.6
2	305.0	349.8	381.8	416.4	464.0	491.2	536.6
3	307.8	353.6	383.4	424.2	461.4	505.4	534.6

5.3 Influence of reading device on the accuracy of results

As can be seen on Figure 16, the volumetric water content measured by Procheck for 5TE sensors as compared to the real value obtained by the gravimetric method seem slightly lower at all organic carbon levels including control except for 4C (4% compost) treatment which seem to be quite in line with the real value. The EM50 data logger used for 5TE sensors in the same case as can be seen on Figure 17 shows similar output as described for Procheck above for all replicas. Calculated volumetric water content from the raw counts of ECH2O Check which was used to take readings for EC-5 sensors using the factory calibration equation (see Eq. (4)) however, were a bit closer to the real values though 0% moisture level values in most cases were calculated were negative A graph showing the calculated volumetric water content by the EC-5 sensors against real water content is displayed in Figure 18.

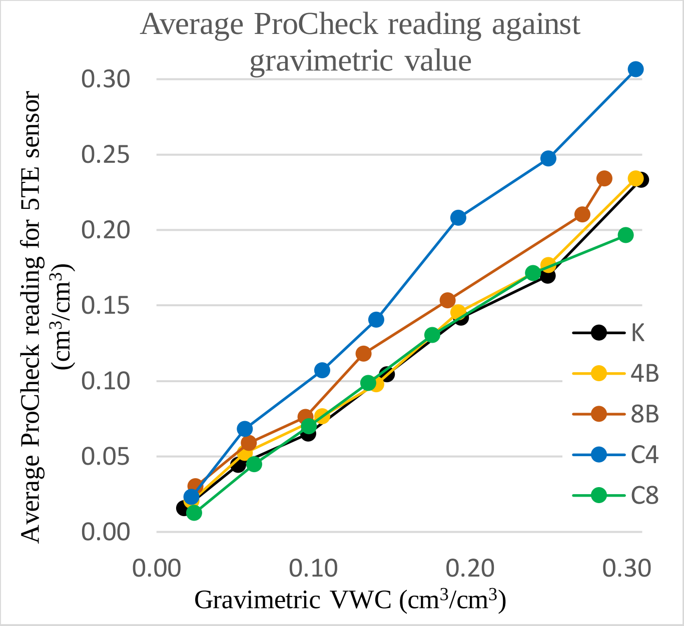

Figure 16: Comparison of average PROCHECK reading for 5TE sensors and real volumetric water content obtained by gravimetric method for various moisture levels and various organic carbon levels of Biochar and Compost mixed soil.

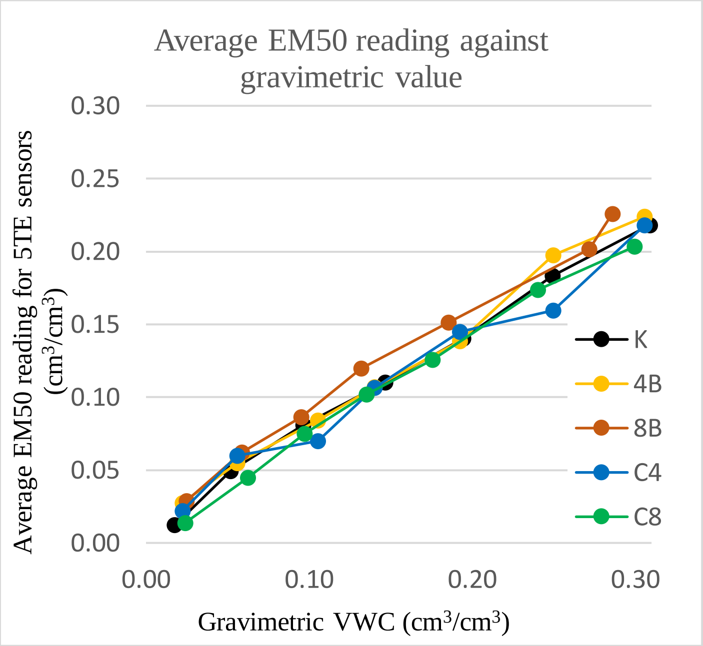

Figure 17: Comparison of average EM50 data logger reading for 5TE sensors and real volumetric water content obtained by gravimetric method for various moisture levels and various organic carbon levels of Biochar and Compost mixed soil.

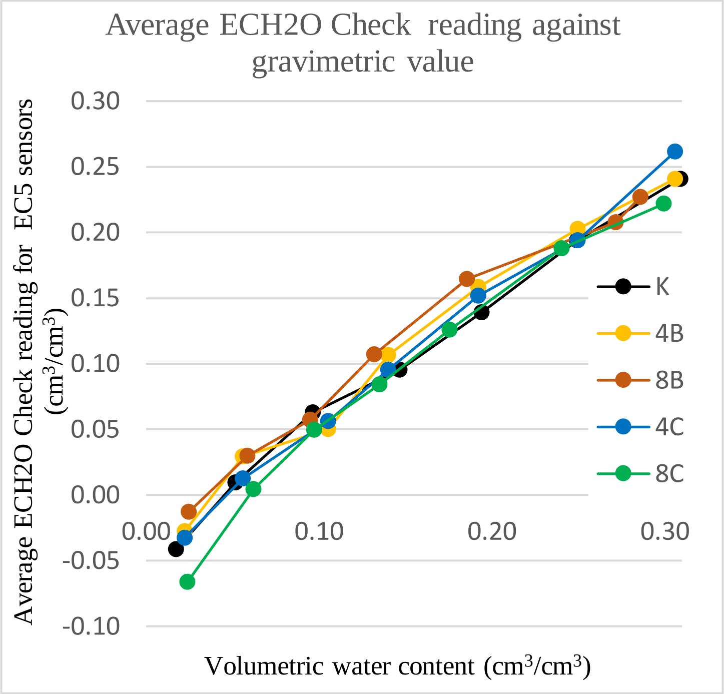

Figure 18: Comparison of average ECH2O CHECK reading for EC-5 sensors and real volumetric water content obtained by gravimetric method for various moisture levels and various organic carbon levels of Biochar and Compost mixed soil

The statistical analysis in Table 5 shows statistical difference in the output of reading devices during measurements at nearly dry conditions of the control and 8% organic carbon treatments from 0% to 15% moisture levels and 8% compost treatment at 20% moisture level. In all cases however, the EM50 data logger and the ProCheck have a very good significant similarity. This could be because they were al used to measure water content by the 5TE sensors. The ECH2O Check however, recorded high values in millivolts in all cases making it to be significantly different from the others.

Table 5: ANOVA comparing the significant statistical difference between raw count volumetric water content recorded at each moisture level by each reading device at 8% organic carbon level.

Reading device		**EM50**	**Procheck**	**ECH2O Check**
0% VWC	**K**	117b	128b	**302a**
	8B	170b	155b	**326a**
	8C	119b	123b	**281a**
5% VWC	**K**	188b	181b	**345a**
	8B	215b	208b	**362a**
	8C	179b	182b	**341a**
10% VWC	**K**	252b	219b	**390a**
	8B	264b	240b	**385a**
	8C	240b	229b	**379a**
15% VWC	**K**	313b	296b	**417a**
	8B	337b	324b	**427a**
	8C	297b	282b	**408a**
20% VWC	**K**	384	376	454a
	8B	410	401	475a
	8C	350b	350b	**443a**
25% VWC	**K**	487	439	493a
	8B	537	544a	504
	8C	463	442	495a
30% VWC	**K**	614a	612	539
	8B	602	613a	528
	8C	540a	507	523

5.4 Influence of organic matter on the accuracy of results

The data from the control experiment, K was compared with data from the biochar and compost mixed soil represented by B and C respectively as described above to examine the influence of organic carbon on the sensor reading in all replicas.

ANOVA statistics as represented in Tables 3, 5, 6, 7 and 8 shows a significant statistical difference (indicated by red color) and no significant statistical difference (indicated by black color).

However, a statistically significant difference can be observed in Table 6 for 8B (8% Biochar) treatment in raw values for 0% and 25% moisture levels. Besides, even though it is not significantly different in the rest of the moisture levels, 8B treatment caused the highest mV (millivolts) values among nearly all measurement levels for volumetric water content, (VWC) except for 30% moisture level as can be seen on. Moreover, in the same Table 6, 8C (8% Compost) treatment on the other hand, has the lowest mV value in almost all moisture levels except for 0% and 25%. 4% organic carbon treatments for both Biochar and Compost treatments showed similar result and did not reveal any solid meaningful pattern except for dry control soil thus 0% and 25% moisture level where 4B (4% Biochar) and 4C (4% Compost) were statistically the same at 0% moisture level and statistically different at 25% moisture level.

4C and the 8C also exhibited a statistical similarity with the dry control soil at 0% moisture level and 25% moisture levels. In short, a statistical similarity can be observed between individual organic matter level measurements with the control though among them (4% and 8%), there is a statistical difference.

Table 6: ANOVA comparing the significant statistical difference between raw count volumetric water content recorded at each organic carbon level by EM50 data logger for 5TE sensors.

EM-50 Data logger	0 % VWC	5% VWC	10% VWC	15% VWC	20% VWC	25 % VWC	30 % VWC
	mV						
OC-2K	117.0 c	188.4	252.2	313.4	383.8	487.2 ab	614.2 a
OC-4B	146.6 b	191.4	259.2	307.8	381.8	525.5 a	595.8
OC-8B	**169.6 a**	214.6 a	264.2 a	337.0 a	410.4 a	**537.4 a**	602.4
OC-4C	135.2 bc	208.8	230.0	318.8	394.0	429.2 b	584.4
OC-8C	119.0 c	179.2	240.2	296.8	349.8	463.2 ab	539.8

Statistics of ProCheck output in Table 7 also shows that 8B treatment, again, caused the highest mV values among all treatments. A statistical difference can be observed at moisture levels; 0%, 5%, 15% and 25%. These higher values can be attributed to the inert and stable structure of pyrolytic materials in biochar. Also, 8C values were found to be lower again, as compared to control and 8B treatments, especially in nearly dry conditions. 4% organic carbon treatments for both biochar and compost did not cause any statistical difference comparing to control and among each other. There is however a statistical similarity between 8B and 4C at 5% and 15% moisture levels.

Table 7: ANOVA comparing the significant statistical difference between raw count volumetric water content recorded at each organic carbon level by ProCheck for 5TE sensors.

Procheck	0% VWC	5 % VWC	10 % VWC	15 % VWC	20 % VWC	25 % VWC	30 % VWC
	mV						
OC-2K	128.4 b	180.8 b	219.6	296 b	376.0	439.4 b	611.6
OC-4B	137.0 b	196.0 ab	241.8	282.8 b	382.4	456.4 b	611.8
OC-8B	**155.0 a**	**207.8 a**	240.4	**324.2 a**	401.4 a	**543.6 a**	613.0 a
OC-4C	132.8 b	200.0 ab	241.8 a	303.2 ab	387.0	436.4 b	606.2
OC-8C	122.6 b	181.8 b	229	282.4 b	349.8	442.4 b	506.4

ECH2O Check recorded raw values for EC-5 sensors and statistics revealed that in nearly dry conditions of 0% to 15 % moisture levels, 8B treatment again recorded the highest mV values as can be seen in Table 7. Moreover, 8C was found to have the lowest mV values by significant statistical difference in all cases of moisture levels except for 25% with no statistical difference. 4% organic carbon treatments for both biochar and compost showed similar effects and are significantly the same in all aspects of moisture levels. There were higher values of raw counts in 4B treatments comparing to values obtained for the control experiment for moisture levels of 0%, 5% 15% and 20%. There is an exceptional statistical difference observed for 8C at 0% moisture level. This can be attributed to the higher volume of soil packed for that organic matter and moisture level that may possibly cause some errors due to difficulty in packing. The control soil at 0% moisture level has no significant similarity with any other treatment at that moisture level but however has a significant similarity with 4B and 4C organic carbon treatments at moisture levels of 15%. 20% and 30%.

Table 8: ANOVA comparing the significant statistical difference between raw count volumetric water content recorded at each organic carbon level by EH2O Check for EC-5 sensors.

ECH2O Check	0 % VWC	5% VWC	10% VWC	15% VWC	20% VWC	25 % VWC	30 % VWC
	mV						
OC-2K	302.3 c	345.0 b	390.0 a	417.3 ab	454.0 bc	492.7	539.3 ab
OC-4B	313.7 b	361.7 a	379.3 b	426.7 a	470.0 ab	502.3	539.3 ab
OC-8B	**326.3 a**	**362.0 a**	**385.0 ab**	**427 a**	**475.3 a**	504.0 a	527.7 b
OC-4C	309.7 bc	347.7 b	384.3 ab	417.3 ab	464.3 ab	500.0	**556.7 a**
OC-8C	281.3 d	340.7 b	378.7 b	407.7 b	442.7 c	495.0	523.3b

To summarize the results, it can be observed that the application of organic matter at different doses causes variations in sensor reading. The sensors seem to be recording higher values in biochar treated replicas and relatively lower values in compost treated replicas. As can be seen in Tables 6, 7 and 8 above especially for analysis of Procheck and ECH20 raw data represented in Tables 7 and 8, we can clearly see that the effect of organic material in the soil has a significant effect on sensor readings. These results can be said to be indicating the difference between the adsorption abilities of organic materials used. Having said that, we can also say that biochar pushed water towards the sensors because of its inert properties and compost adsorbs water from sensor measurement environment.

Fares et al. (2016b), using similar method used in this experiment but different organic material and reported a negative correlation between organic matter level and average sensor readings with $R^2 = 0.92$. However, in this experiment, there is a strong positive correlation between organic matter level and the average sensor raw counts for biochar mixed soil with r in all cases almost equal to +1 (see figure 19, A and B) and a strong negative correlation in the case of compost mixed soil; thus r in all cases equal to and almost -1 (see figure 20, A and B). This can be interpreted that measured water content as sensor output increases with increasing organic matter content in the cases of biochar and decreases with increasing organic matter content in the case of compost.

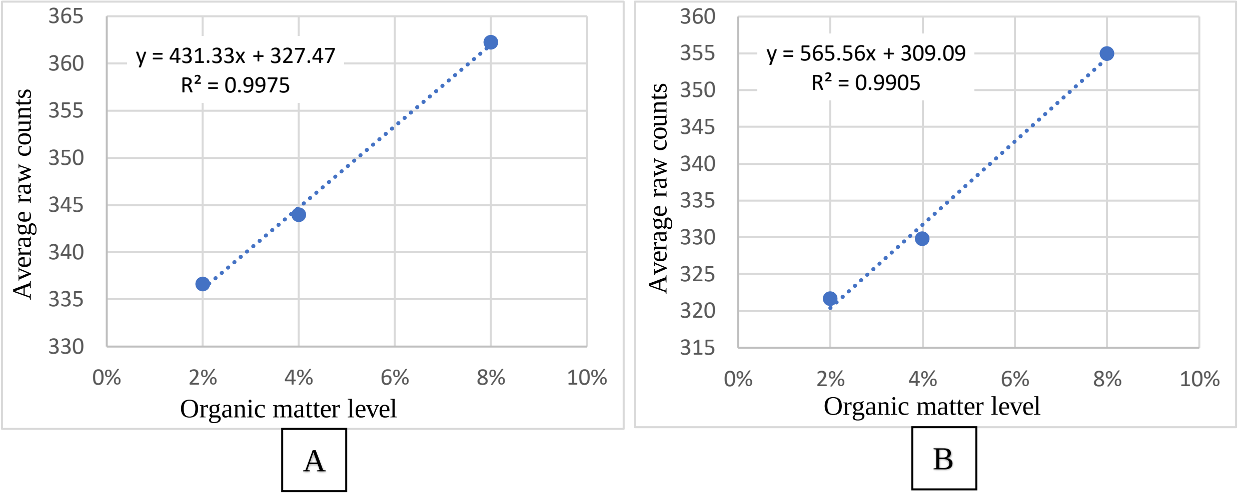

Figure 19: Correlation between organic matter level and average sensor raw count for biochar mixed soil for all moisture levels using (A) EM50 Datalogger and (B) ProCheck

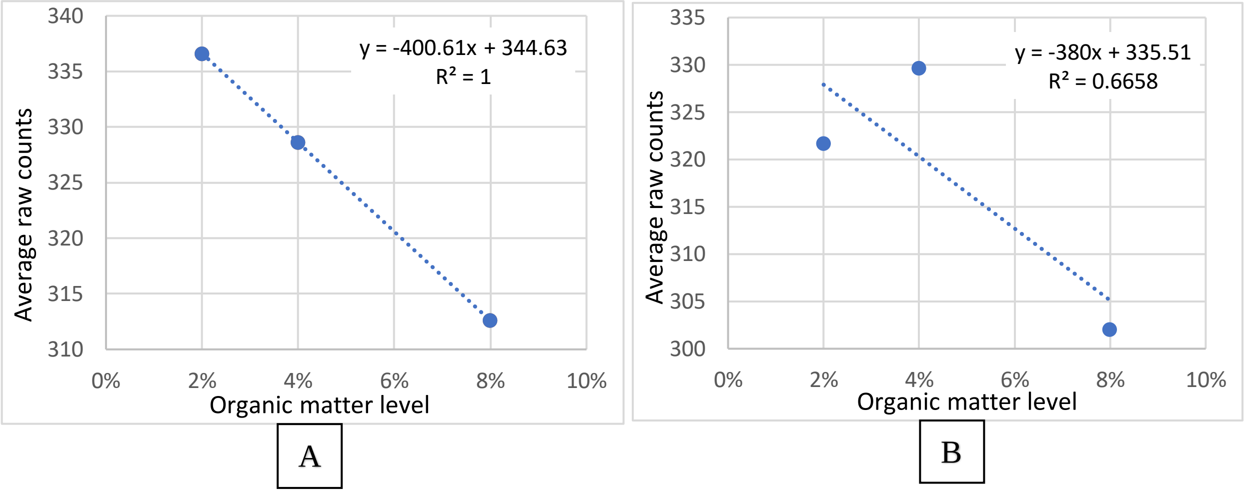

Figure 20: Correlation between organic matter level and average sensor raw count for Compost mixed soil for all moisture levels using (A) EM50 Datalogger and (B) ProCheck

5.5 Own calibration of the sensors

Raw data from the data loggers for the sensor in mV were also collected and their relationship with the volumetric soil water content determined by the gravimetric method in cm^3/cm^3 was observed. Calibration equation were determined using relevant data obtained from the reading devices. Based on the previous findings, 5TE sensor no. 5 was excluded from regression procedure as an apparent outlier. Manufacturer provides for 5TE sensors calibration equations as a polynomial equation of 3rd order, however, for the data obtained in this study polynomial equation of 2nd order is rather sufficient; see Figures 21 and 22. In agreement with previous findings, OM content of 4% does not differ significantly from control and also the differences between biochar and compost are not apparent. Differences are higher at higher water contents.

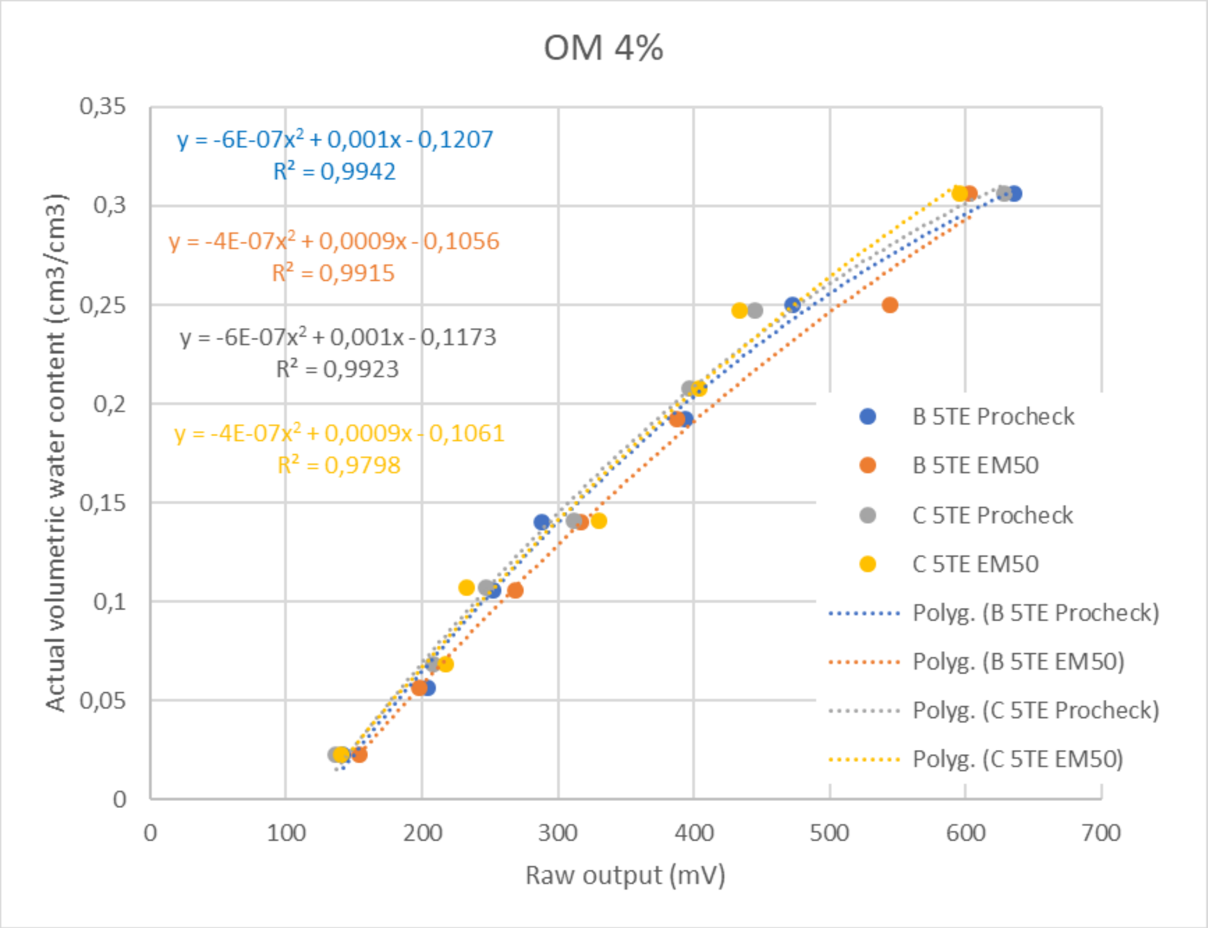

Figure 21: Calibration equations for 5TE sensor for two reading devices and for two added organic materials (4%).

On the other hand, calibration lines for compost and biochar at 8% OM content differ the more the higher is water content (see Figure 22), and raw readings are significantly higher for biochar treated soil. Thus, using the own calibration equations can improve the accuracy of the sensor readings.

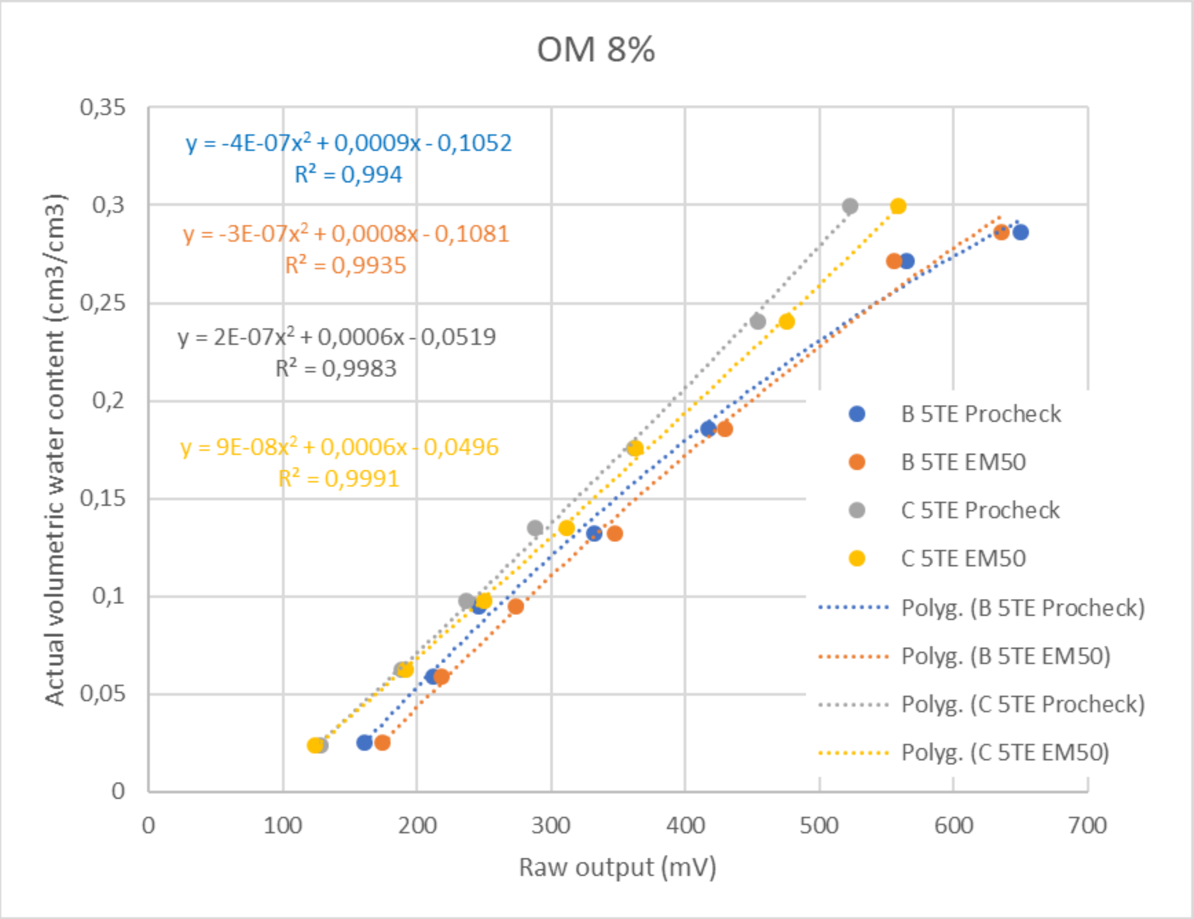

Figure 22: Calibration equations for 5TE sensor for two reading devices and for two added organic materials (8%).

5.6 Supporting basic soil properties

In order to characterize the materials used in this study, some basic properties were determined. Soil electrical conductivity changed linearly by the addition of both organic materials, see Figure 23. Analysis of variance however also shows the results are statistically significant ($p<0.05$). The highest value was found as 1073 µS/cm and this is for OC-8C treatment, and still way lower than the value which can cause an interference of salinity. To support with, Scudiero et al. (2012) investigated the efficiency of low-cost sensors, in which 5TE was part. They subjected these sensors to different salinity conditions by assessing the initial salinity level as 5000 µS/cm. Salinity conditions were also created by much higher salt concentration in another studies (Matula et al., 2016). pH values also changed significantly and created a variety of soil reaction between treatments, from 5.54 to 7.54, and increases with increasing organic carbon level with OC-8C treatment recording the highest average pH without causing any extreme pH value.

Particle size distribution of coarse particles was obtained by dry sieving method, see Figure 24. Soil and compost have very similar particle distribution with proportionally increasing ratio of coarser particles, while biochar has rather high amount of the biggest particles between 1 and 2 mm, but also the finest particles up to 0.1 mm.

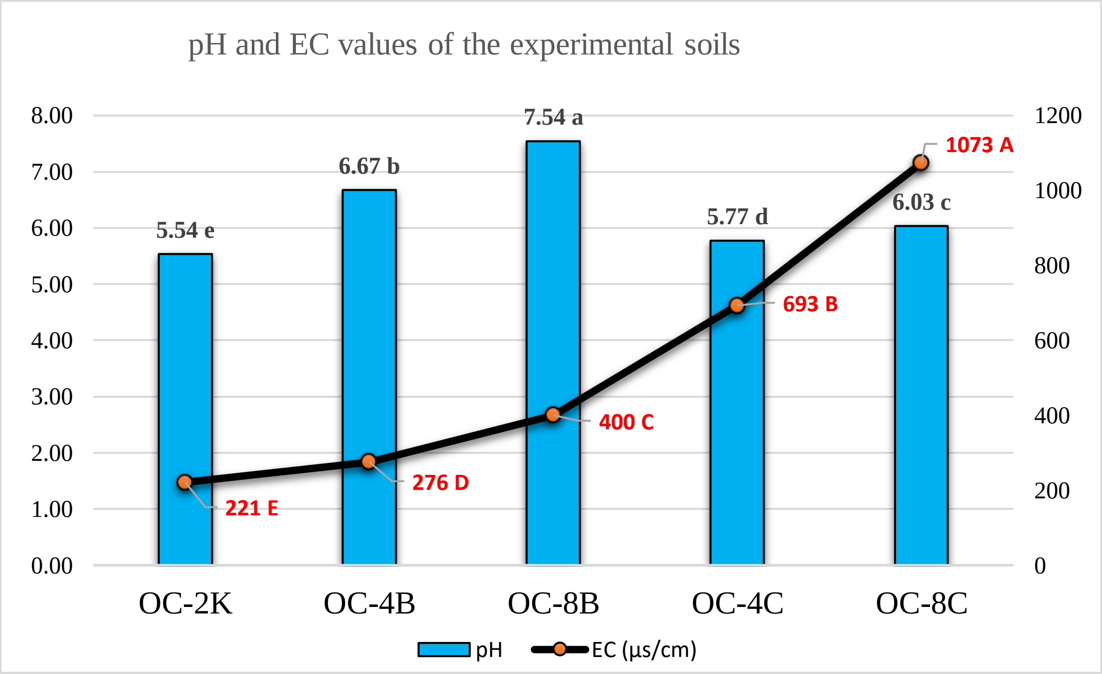

Figure 23: pH and electrical conductivity (EC) analysis of the various soil treatments.

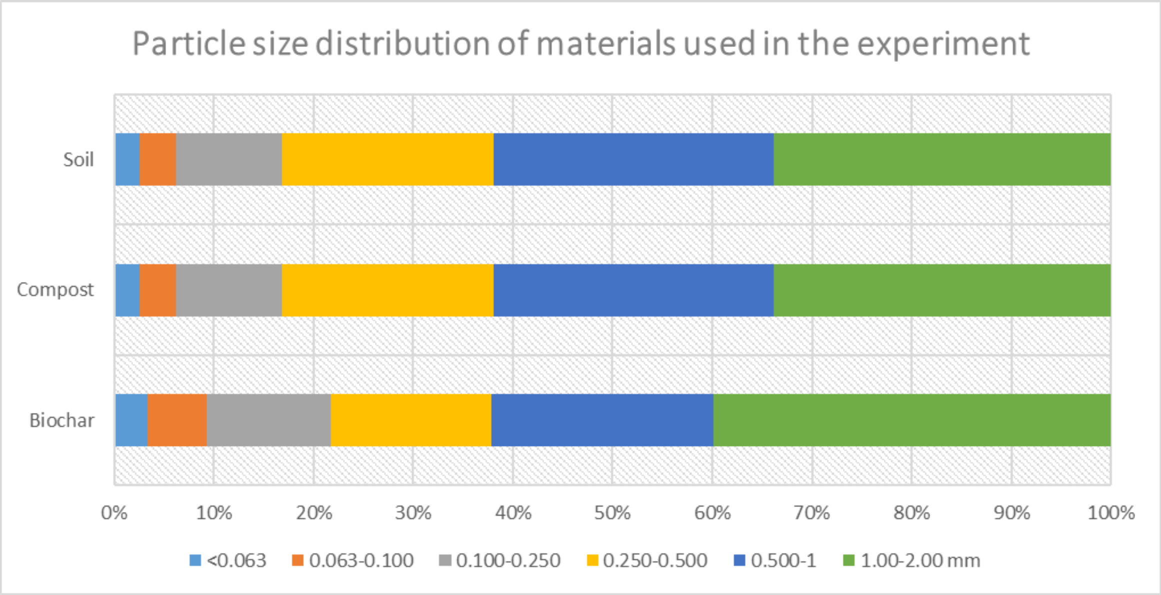

Figure 24: Particle size distribution of the soil and organic materials (biochar and compost) obtained by dry sieving method.

6 Discussion

6.1 Repacking of soil to desired bulk density

No literature so far stated any standard method of repacking of soil to desired bulk density. However, in this experiment, since all measurements were done in the lab and there was the need to treat the soil as if it was originally on the field, repacking was done to desired bulk densities taking into consideration the dry bulk density of the soil initially calculated. Fares et al. (2016) and Matula et al. (2016) however, in their research used a method for preparing repacking of samples similar to what was used in this experiment while aiming at response to organic matter by some selected sensors using sawdust and quartz sand as organic carbon supplements.

6.2 Effects of organic matter on sensor readings

Fares et al. (2016) stated that the effect of organic matter on sensor readings cannot be attributed to the default calibrations provided by the manufacturers. They however, also laid emphasis on the need to develop polynomial calibration equations that should be organic matter specific by using statistical packages and incorporating raw counts and organic matter level as covariates. At the end, they achieved similar results as organic matter interactions significantly affected the sensor readings as can as well be seen in this experiment.

They also, however found out a strong negative correlation between organic matter level and sensor readings as average raw counts of the sensors decreased with increasing organic matter. In the case of this experiment, similar instance can be deduced as it was found out in the case of compost treated soil that average raw counts decreased with increasing organic matter and increased with increasing organic matter level in the case of biochar. Fischer *et al.* (2019) suggested that biochar modified soils tend to increase soil water content with respect to control treatments and that adding biochar to the soil in an idealized scenario shifts the water retention curves towards more positive water potential values at a given volumetric soil moisture level. There is no doubt about that as results from this experiment seem to be in line with that. Therefore, it is reasonable to assume biochar treated soils tend to increase soil water content.

6.3 Calibration equation

The effects observed for these organic matter treatments on sensor output of soil water content gives reason to agree with manufacturers for stating the need for calibration of these sensors according to use in specific soils. For that matter, an own organic-matter-level-specific calibration equation was done to improve the accuracy of the sensors. This calibration type was also carried out by Fares et al. (2016), their research was similar to this improving the accuracy of the default calibration in the range of 5.3% to 7.2% which was determined by RMSD to 1.3% to 1.9%. In the case of this experiment, however, the accuracy of the factory calibration of these sensors as determined by the RMSD was in the range of 3.1% to 7.1%. The new calibration for the two organic materials used at 4% and 8% doses (see figures 21 and 22) showed an average regression around 99% in most cases ($R^2 = 0.99$) except for that of C 5TE EM5O which is around 97%. For that matter, accuracy of the new calibration can be estimated to be around 0.5% to 1%.

Our results concur with the same researchers (Fares et al., 2016) as a significant sensor-to-sensor variation was also demonstrated by their results after statistical analysis. It can be clearly seen that 5TE sensor number 5 especially in this experiment exhibited a huge significant difference between other sensors and for this, we can say there is the possibility of brand-new sensor failures.

On the contrary however, the findings in this experiment, are not so in line with these researchers; (Matula *et al.*, 2016; Parvin and Degré, 2016) who calibrated some of these sensors without observing the effects of organic matter on their performances though they employed a similar method in repacking of the soil samples before taking measurements, as they observed other effects, e.g. salinity.

Sensor-to-sensor variation in reading as assumed in the hypothesis of these experiment stating that it may significantly affect the results of measuring networks can be confirmed from the results as all sensors seem to be giving different output values. Statistical analysis of the results for 5TE sensors by METER Group (see Table 3) obtained also revealed that there is a significant difference between the output of the sensors. However, statistical analysis in Table 4 for ECH20 EC-5 sensors showed no significant difference among the sensors.

Moreover, difference response of sensors via various reading devices as also assumed can be noticed from the results; for instance in the case of 5TE sensors, ProCheck and EM50 datalogger were used to take measurements at the same spot for each sensor and volumetric water content outputs of these reading devices can be observed to be different though statistical analysis of these two reading devices showed significant similarity between them in all aspect of moisture levels as can be seen in Table 5.

Results also showed that application of organic matter from the two sources used (Biochar and Compost) to increase organic carbon content of the soil has a significant effect on the measuring accuracy as it can be observed that these organic matter sources upon application with the same moisture level treatment yielded different outputs. The correlation between these organic carbon sources with real water content obtained by gravimetric method as can be seen in Figures 19 and 20 was earlier described in chapter 5.4.

In addition, the compost adsorbs water in soil, and this adsorption creates a competition between retainers. The water in sensor measurement area in most cases were adsorbed by compost and this was revealed in mV reading being lower compared to the treatment condition without a retainer (compost). In the case of biochar, however, there was no adsorption but rather, it acted inertly so the solid volume of the stabile and inert biochar pushed the water to the sensor area hence increasing mV values and calculated VWC.

These researchers reported overestimation of the sensors used in this experiment; (Varble and Chávez, 2011) for 5TE sensors and (Ojo et al., 2014) for EC-5 sensors and they however commented that the overestimation of these sensors was dependent on the volumetric water content in the soil. This could be argued since findings from this experiment shows that organic matter content plays role in sensor output and there was rather an underestimation of real volumetric water content which concur with findings by Fares et al., (2016).

6. Conclusions

This study dealt with dielectric soil moisture sensors' calibration in laboratory condition on homogeneously repacked soil with prepared water content. 5TE and EC-5 soil moisture sensors are widely used, yet there can appear inconsistency in readings caused e.g. by differences between individual sensors or influenced by various substances, e.g. organic matter. Producers always recommend an individual calibration, if very accurate results are needed, however, it is not always possible, thus a factory calibration is often used.

The calibration of sensors in this work has been seen from several aspects. Firstly, sensor-to-sensor precision was tested while different reading devices were used, and secondly, the influence of amount and type of organic matter admixtures was carefully observed. The latter has been very little investigated so far, thus the results have impact into practice.

First hypothesis about sensor-to-sensor differences was confirmed, one of the five tested 5TE sensors registered consistently and statistically significantly ($p<0.05$) lower values than others. On the other hand, there was statistical difference between reading devices ProCheck and EM50 datalogger. But both of them differed from ECHO Check device operating the EC-5 sensors.

Second hypothesis about influence of organic matter to the sensor response was confirmed. Two types of organic matter were added, compost and biochar, each in doses achieving 4% and 8% of OM content. Untreated soil (control) had 2.07% of OM. Strong positive correlation was found for biochar treated soil, the raw sensor output increased with increasing biochar OM content, and strong negative correlation was found for compost treated soil.

Effect of OM can be quantified in terms of RMSD, where the measurement accuracy achieved from 3.1 to 7.1 % vol. when factory calibration was used, while RMSD decreased to 0.5 to 1 % vol. when own new 2nd order polynomial calibration equation were used.

Based on the results listed above, it can be concluded that objectives of the thesis were fulfilled.

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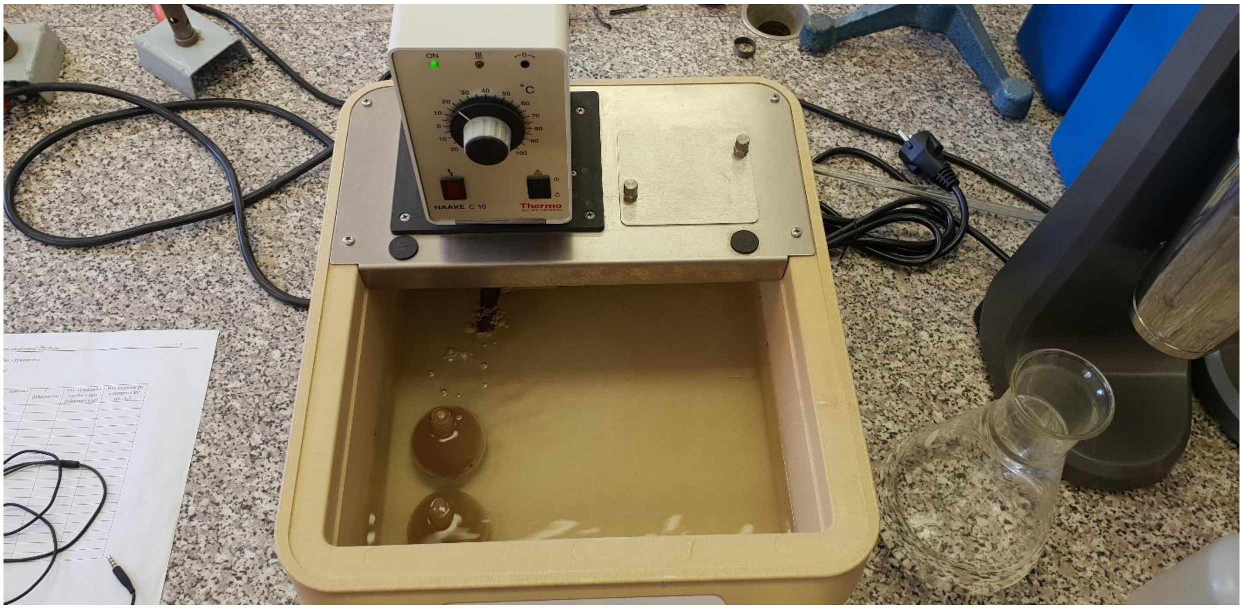
List of Appendices

Appendix

Appendix 1: Soil sample being air dried.

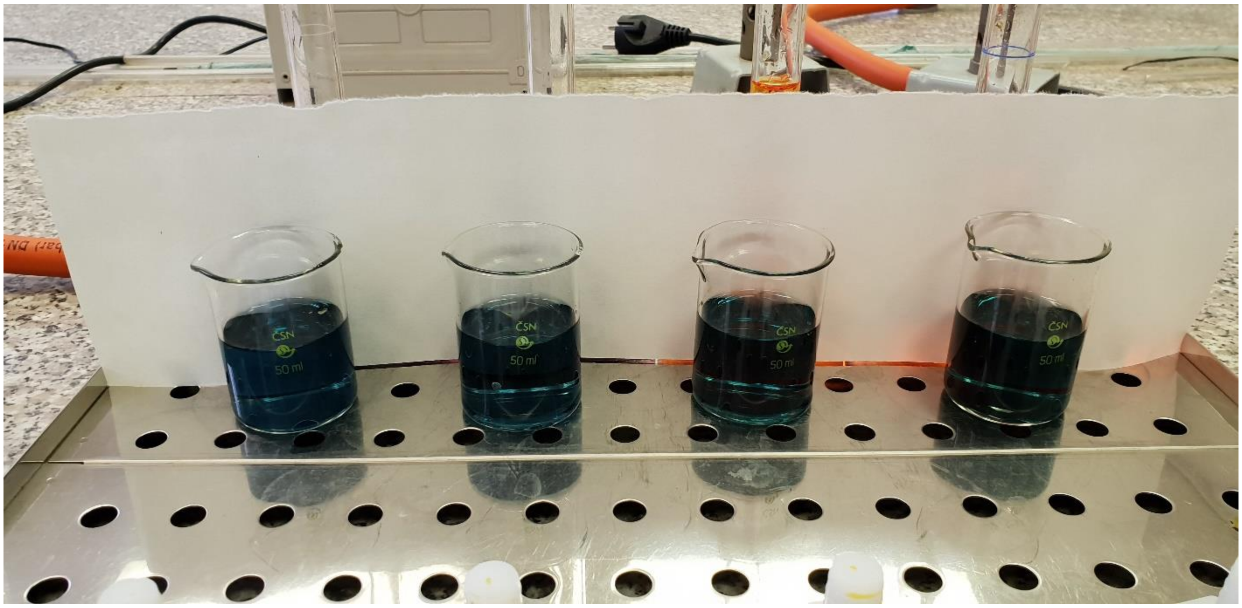
Appendix 2: Farm-made compost being air dried.

Appendix 3: Air dried soil sample being sieved with a 2 mm sieve.

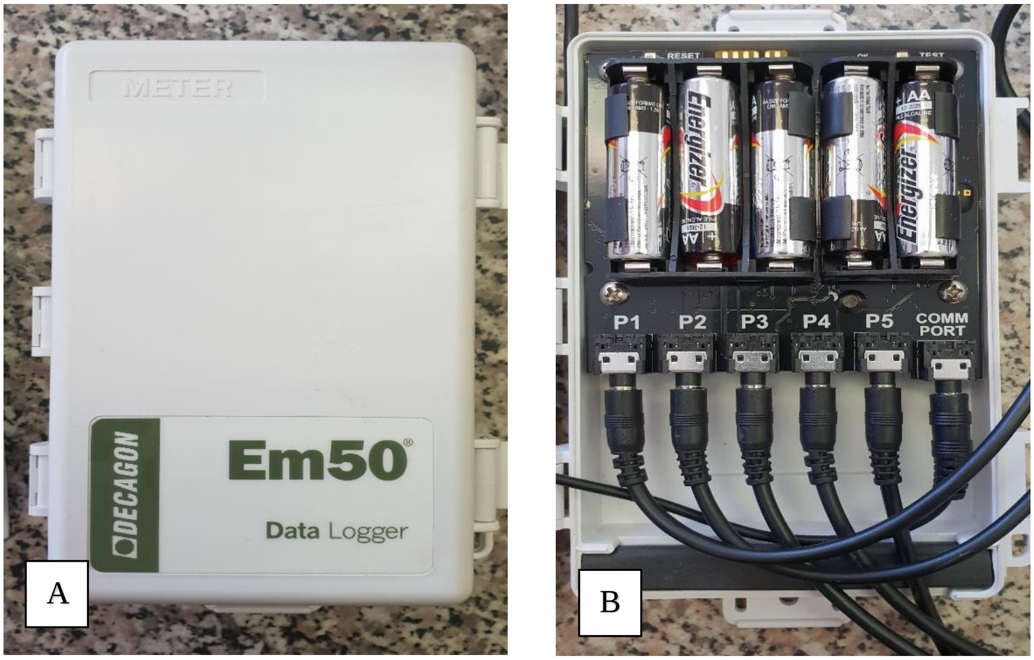


Appendix 4: Pycnometer in temperature bath (20^{o}C) for particle density determination.

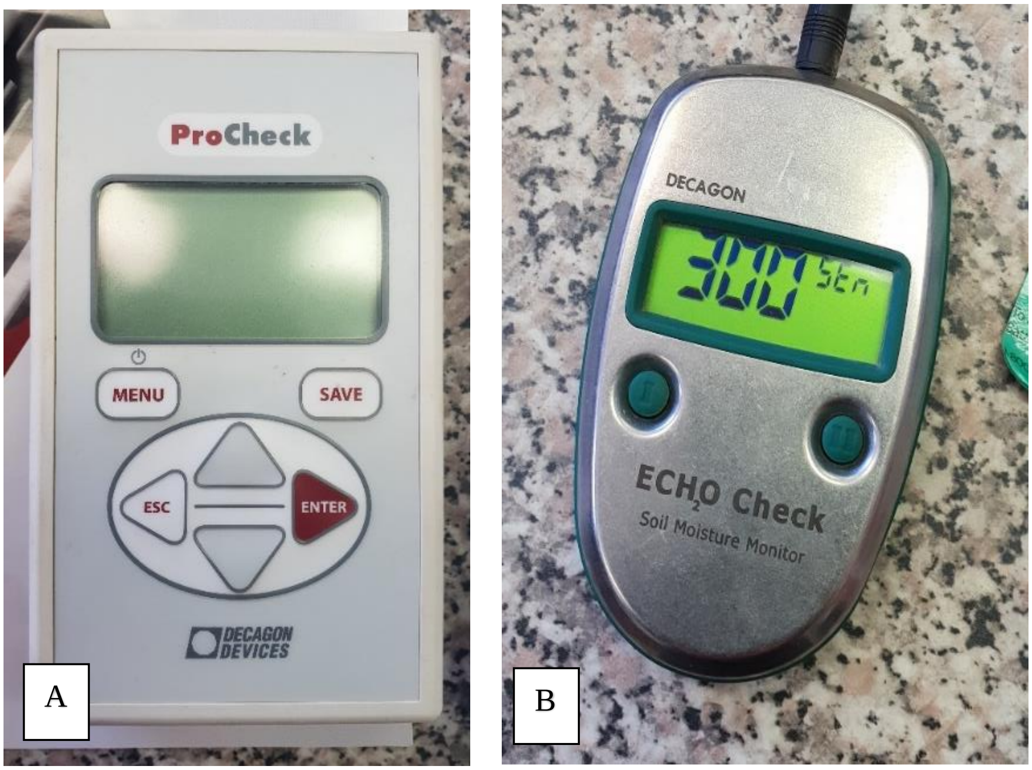
Appendix 5: Organic carbon content determination using a modified Walkley-Black method.



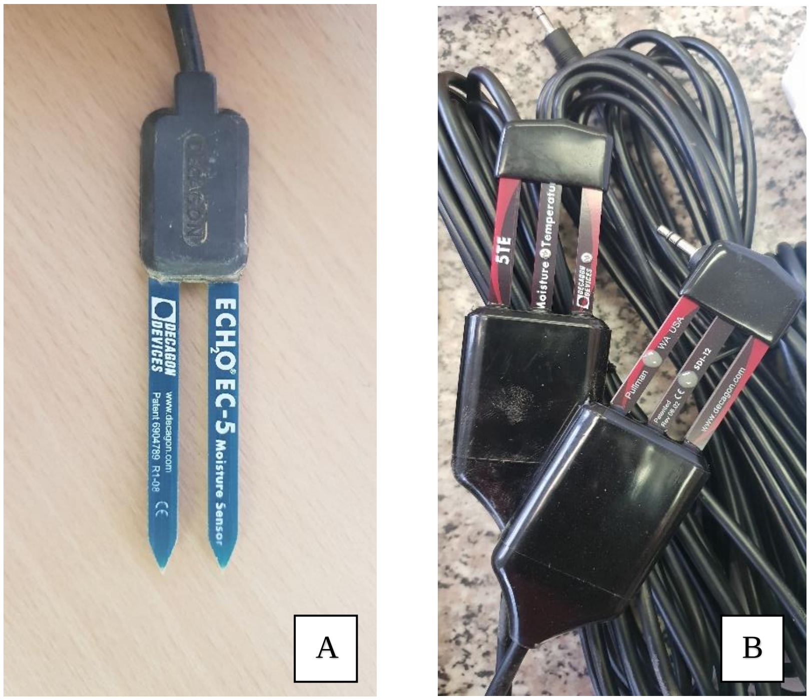
Appendix 6: Colour change of sample under the above Organic carbon content determination.



Appendix 7: (A) Exterior of EM50 Data Logger (B) Interior of EM50 Data Logger.



Appendix 8: (A) ProCheck data Logger (B) ECH$_2$O Check reading device.

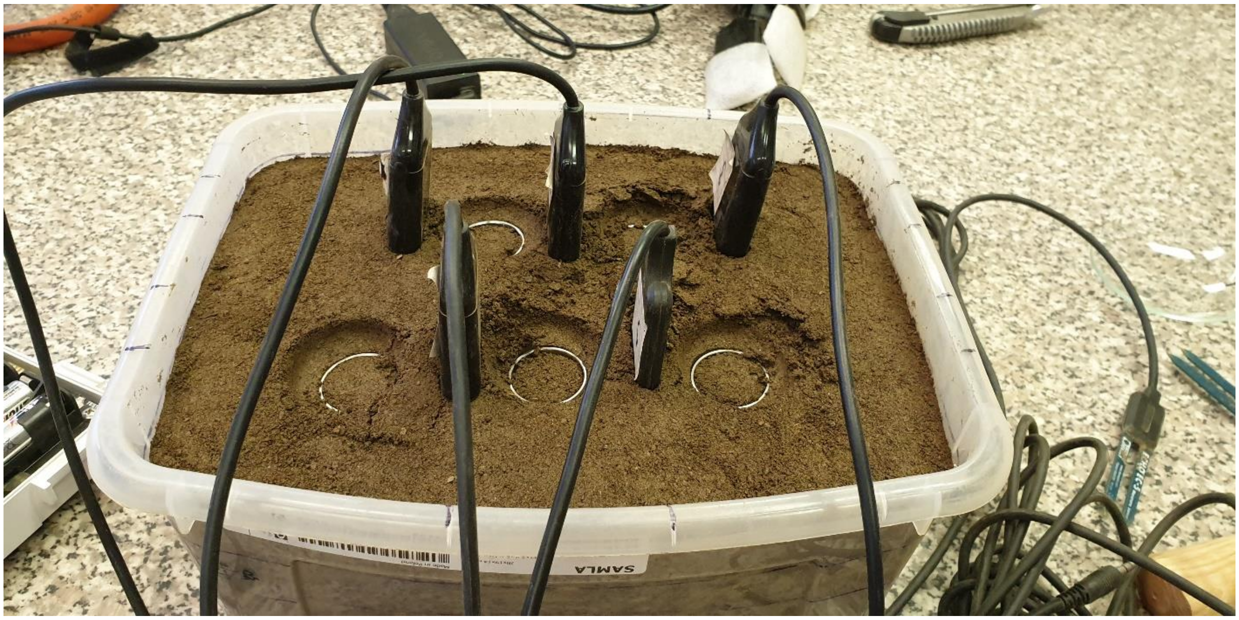


Appendix 9: (A) ECH$_2$O EC-5 moisture sensor (B) 5TE moisture sensor.

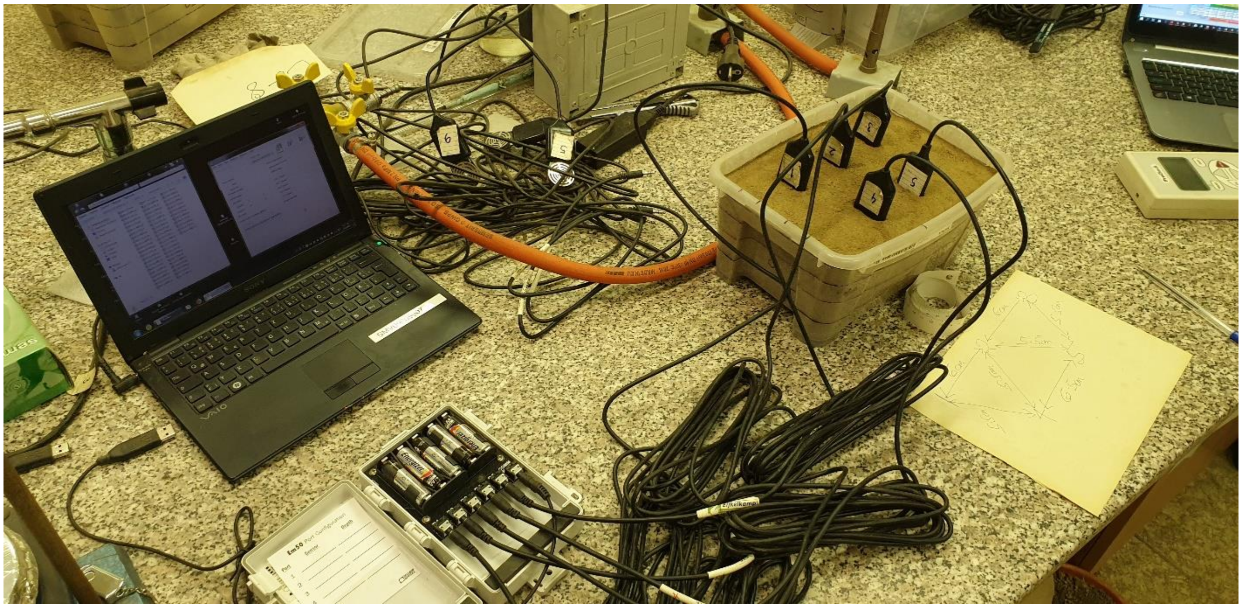
Appendix 10: (A) Hammer used for pusing the sampling rings into the soil sample (B) Sampling rings.

Appendix 11: Homogeneus mixing of soil before packing into sampling bowl

Appendix 12: Soil packed into the sampling bowl to the third level of desired bulk density.

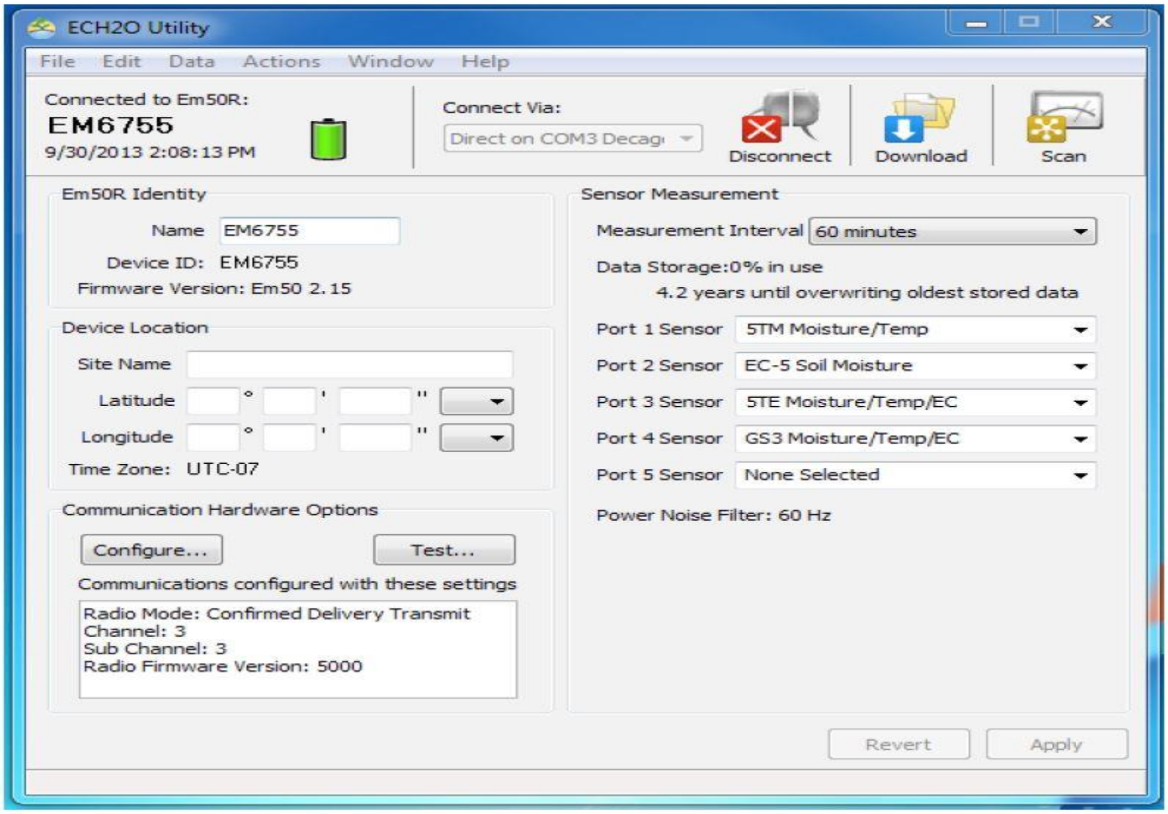


Appendix 13: Sampling with sample rings after taking sensor readings



Appendix 14: View of experimental setup

Appendix 15: Samples placed in oven at a temperature of 105^{o}C for volumetric water content determination



Connected to Em50R:
EM6755
9/30/2013 2:08:13 PM

Connect Via: Direct on COM3 Decag

Em50R Identity

Name: EM6755
Device ID: EM6755
Firmware Version: Em50 2.15

Device Location

Site Name
Latitude ° ' "
Longitude ° ' "
Time Zone: UTC-07

Communication Hardware Options

Communications configured with these settings

Radio Mode: Confirmed Delivery Transmit
Channel: 3
Sub Channel: 3
Radio Firmware Version: 5000

Sensor Measurement

Measurement Interval: 60 minutes
Data Storage:0% in use
4.2 years until overwriting oldest stored data
Port 1 Sensor: 5TM Moisture/Temp
Port 2 Sensor: EC-5 Soil Moisture
Port 3 Sensor: 5TE Moisture/Temp/EC
Port 4 Sensor: GS3 Moisture/Temp/EC
Port 5 Sensor: None Selected
Power Noise Filter: 60 Hz

Appendix 16: ECHO Utility software in operation for water content measurement.