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Soil moisture sensor calibration for organic soil surface layers

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Abstract

This paper's objective is to present generic calibration functions for organic surface layers derived for the soil moisture sensors Decagon ECH2O 5TE and Delta-T ThetaProbe ML2x, using material from northern regions, mainly from the Finish Meteorological Institute's Arctic Research Center in Sodankylä and the study area of the Danish Center for Hydrology HOBE. For the Decagon 5TE sensor such a function is currently not reported in literature. Data were compared with measurements from underlying mineral soils including laboratory and field measurements. Shrinkage and charring during drying were considered. For both sensors all field and lab data showed consistent trends. For mineral layers with low soil organic matter (SOM) content the validity of the manufacturer's calibrations was demonstrated. Deviating sensor outputs in organic and mineral horizons were identified: for the Decagon 5TE apparent relative permittivities at a given moisture content decreased for increased SOM content, which was attributed to an increase of bound water in organic materials with large surface areas compared to the studied mineral soils. ThetaProbe measurements from organic horizons showed stronger non-linearity in the sensor response and signal saturation in the high level data. The derived calibration fit functions between sensor response and volumetric water content hold for samples spanning a wide range of humus types with differing SOM characteristics. This strengthens confidence in their validity under various conditions, rendering them highly suitable for large-scale applications in remote sensing and land surface modeling studies. Agreement between independent Decagon 5TE and ThetaProbe time series from an organic surface layer at the Sodankylä site was significantly improved when the here proposed fit functions were used. Decagon 5TE data also well-reflected precipitation events. Thus, Decagon 5TE network data from organic surface layers at the Sodankylä and HOBE sites are based on the here proposed natural log fit. The newly derived ThetaProbe fit functions should be used for hand-held applications only, but in that case proof of value for the acquisition of instantaneous large-scale soil moisture estimates.

1 Introduction

The circumpolar northern colder climate zone (boreal forest and tundra) contributes with a substantial fraction to the total global landmass. Because of slower decomposition rates in these regions pronounced organic layers have been accumulating on top of the mineral soils. Particularly when frozen, organic-rich soils store a significant amount of carbon acting as important sinks. However, the higher Northern latitudes are especially sensitive to climate change (IPCC, 2007) due to above-average rising temperatures (e.g. Hansen et al., 2006). Thus, a considerable positive feedback on global warming is likely once additional carbon is respired from thawing grounds (Stokstad, 2004). The prediction of the overall response of these ecosystems to global warming is currently highly uncertain. In this context, hydrological processes play a key role and soil moisture is one of the main factors to be assessed to understand and quantify the processes and feedback mechanisms controlling water, energy, and carbon fluxes at the land surface–atmosphere interface.

Given the particular hostility and remoteness of high latitude environments, space-borne remote sensing techniques together with land surface modeling constitute essential tools for soil moisture observations at high temporal resolution and with complete spatial coverage (e.g. Reichle et al., 2007; Albergel et al., 2012). Nevertheless, spatially distributed in situ soil moisture measurements are indispensable for the Calibration/Validation (Cal/Val) activities of these global soil moisture products as well as in order to increase process-understanding at local scale.

Electromagnetic based sensors belong to the most popular in situ soil moisture measuring techniques, as they can be used for automated continuous measurements at high temporal resolution in most soil types and plant growth substrates, including shallow recordings close to the surface. Different sensor types have been developed using capacitance and impedance as well as Time or Frequency Domain Reflectometry and -Transmissometry (TDR, FDR, and TDT, FDT) methods. The shape and design of the sensors as well as the measurement and/or raw data “interpretation” is highly variable

(Robinson et al., 2008). Nevertheless, they all take advantage of the large difference between the relative permittivity (ε; relative to free space, also referred to as dielectric constant) of dry soil and water in order to estimate the volumetric fraction of the latter (e.g. Topp, 2003; Robinson et al., 2003). ε is a complex number whose real part ε' expresses energy storage based on the ability of a particle to align with the electric field. The imaginary part ε'' describes energy losses due to absorption and electrical conductivity. In the frequency range where most electromagnetic sensors operate the measured relative permittivities mainly correspond to ε'. However, as ε'' contributes to a certain degree to the signal and because the observed relative permittivity is the bulk value of compound solid, gaseous, and liquid constituents, it is usually termed apparent relative permittivity ε_a (e.g. Blonquist et al., 2005).

In case of all electromagnetic sensors the measured raw signal of a substrate is closely related to ε_a, from which the soil moisture can be derived using either dielectric mixing models or empirical calibration equations (e.g. Jones et al., 2002; Nagare et al., 2011). These relations are affected by the sensor design, and thus, are sensor type specific. Manufacturers generally provide default calibrations, often including both, raw signal to soil moisture as well as ε_a to soil moisture relationships. Though calibrated and validated over a wide range of soil types there is general consensus that these functions cannot hold for all conditions, and therefore, soil- and site-specific calibration is often required to improve the measurement accuracy (e.g. Walker et al., 2004; Czarnomski et al., 2005; Blonquist et al., 2005; Evett et al., 2006; Dorigo et al., 2011; Mittelbach et al., 2012; Vaz et al., 2013).

Currently available impedance and capacitance sensors operate at frequencies between 20–300 MHz, while TDR/FDR and TDT/FDT mainly function in the GHz range (Vaz et al., 2013). The latter are generally considered more accurate with less signal contribution of ε'' and hence, reduced sensitivity to salinity (electrical conductivity), temperature, and soil type effects (e.g. Blonquist et al., 2005; Kelleners et al., 2005; Saito et al., 2009). However, the former are often cheaper and power consumption is lower. Given the high spatial and temporal soil moisture variability throughout scales (e.g. Western et al., 2002; Famiglietti et al., 2008), there is broad agreement concerning the benefit of increasing soil moisture network density using cheaper sensors at the cost of accuracy, in order to better represent large-scale satellite footprints and model grid cells (e.g. Czarnomski et al., 2005; Bogena et al., 2007; Kizito et al., 2008; Dorigo et al., 2011; Mittelbach et al., 2012).

Generally, many authors found manufacturer's default calibrations sufficiently accurate for various mineral soil types of differing texture (apart from very clayey soils), while many studies concluded that specific calibrations are crucial concerning organic-rich soils and humus horizons (e.g. Topp et al., 1980; Herkelrath et al., 1991; Roth et al., 1992; Paquet et al., 1993; Jones et al., 2002; Pumpanen and Ilvesniemi, 2005; Kizito et al., 2008; Sakaki et al., 2011; Vaz et al., 2013). Organic material differs from mineral by it's complex structures and small bulk densities. The resulting high porosities and large surface areas result in two effects: (1) substantial water holding capacities up to 0.8–0.9 $cm^3\,cm^{-3}$ compared to around 0.4–0.6 $cm^3\,cm^{-3}$ in case of mineral soils (e.g. Kellner and Lundin, 2001; Li et al., 2004), and (2) a higher amount of bound water altering ε_a (Jones et al., 2002). Water molecules in the vicinity of solid surfaces are subjected to interfacial forces hindering their rotation. Consequently, their ability to align with the applied electric field, and thus, ε, are reduced. Therefore, the water layer closest to the solid particles exhibits a relative permittivity similar to water fixed in ice structures with $\varepsilon' \approx 3$ (Wang and Schmugge, 1980), while in subsequent layers the value gradually approaches the one of free liquid water. Hence, the use of a calibration function for mineral soil leads to a significant underestimation of the actual moisture content in large surface area organic substrates with increased bound water fraction (e.g. Topp et al., 1980; Roth et al., 1992; Paquet et al., 1993). The relative permittivity of the dry solid particles are reported to range between 2 and 5 without a clear difference between organic and mineral substrates (e.g. Topp et al., 1980; Roth et al., 1990; Malicki et al., 1996). This lead to the assumption that ε_{solid} has only little effect on ε_a (Yu et al., 1999).

The influence of organic matter on the TDR response has been studied by many authors (e.g. Topp et al., 1980; Roth et al., 1990, 1992; Herkelrath et al., 1991; Pepin et al., 1992; Paquet et al., 1993; Malicki et al., 1996; Börner et al., 1996; Myllys and Simojoki, 1996; Schaap et al., 1996; Kellner and Lundin, 2001; Jones et al., 2002; Pumpanen and Ilvesniemi, 2005; Shibchurn et al., 2005; Nagare et al., 2011; Vasquez, 2013). However, for other electromagnetic sensors such analysis are more scarce in literature. Recently, Vaz et al. (2013) evaluated standard calibrations for eight electromagnetic sensors. They pointed to the rarity and thus necessity of further investigations on the capacitance and impedance sensor response in substrates of varying organic matter content.

At the Finnish Meteorological Institute's Arctic Research Center (FMI-ARC) in Sodankylä, Northern Finland, the exploration of hydrological processes is one of the multidisciplinary key research topics. On this site there are several projects dealing with the characterization of moisture content in organic-rich soil surfaces as well as freeze–thaw characteristics using different remote sensing techniques as well as land surface modeling (e.g. Rautiainen et al., 2012 and 2014; European Space Agency: ESA SMOS+ Innovation Permafrost, ESA CCI Soil Moisture, ESA SMOSHiLat; National Aeronautics and Space Administration: NASA SMAP Cal/Val). To support these activities an in situ soil moisture network (Ikonen et al., 2015) was installed. It was designed in a similar fashion as the network in the Skjern River Catchment, Denmark (Bircher et al., 2012a), maintained by the Danish Center for Hydrology HOBE, and with related actions ongoing. Therefore, a joined effort aimed at calibrating the used soil moisture sensors, namely, the capacitance Decagon ECH2O 5TE sensor (Decagon 5TE)[1] and the impedance Delta-T ThetaProbe ML2X (ThetaProbe)[1], for organic substrate. At both sites, the Decagon 5TE sensors are installed at the permanent network stations providing data to the International Soil Moisture Network (ISMN, Dorigo et al., 2011) – a global in-situ soil moisture database to support validation and improvement

[1]Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors.

of satellite observations and land surface models. Meanwhile, ThetaProbes are used for hand-held measurement campaigns (e.g. Bircher et al., 2012b), a current method for spatial variation studies of soil water content at different scales (e.g. Baggaley et al., 2009; Lopez-Vicente et al., 2009) and thus, frequently applied in the scope of satellite validation (e.g. Cosh et al., 2005; Kurum et al., 2012).

With the purpose of serving coarse resolution satellite remote sensing and land surface modeling studies, the objective was to provide generic calibration functions holding for different types of organic material as encountered within the large areas under consideration. Necessarily these functions hold a decreased degree of detail and might lack high accuracy, but will clearly outperform default calibration functions provided by the manufacturers. Additionally, they should be applicable without requiring auxiliary information for the large area of interest, such as bulk density/porosity or specific surface area/bound water fraction, as integrated in more sophisticated calibration methods (e.g. Malicki et al., 1996; Dirksen and Dasberg, 1993).

This article presents the Decagon 5TE and ThetaProbe sensor calibrations for organic soil surface layers, derived from field and laboratory measurements using soils from different locations in northern regions, mainly including the Sodankylä and HOBE network areas. While some ThetaProbe calibration efforts are present in literature for organic material from natural soils (see Sect. 3.2), to the knowledge of the authors so far no equivalent studies have been reported in case of the Decagon 5TE sensors. It seems that only Vaz et al. (2013) had looked into the issue for this sensor type, however, using artificial organic material in a limited water content range. Thus, the goal here was to extend the range of validity of the 5TE calibration function for a variety of natural organic substrates and create something more widely applicable.

To avoid inconsistencies, the same measurement and calibration protocol was followed at all sites. The developed fit functions were evaluated against the manufacturers' calibrations as well as earlier published fitting functions. Furthermore, soil moisture time series from both sensors collected at two Sodankylä network sites were compared, using both manufacturer's default and our own derived calibrations. Measurements from the underlying mineral soil layers with variable soil organic matter content were also considered in order to demonstrate the validity of the manufacturer calibrations within those layers.

2 Description of study sites and data

Figure 1 gives an overview of the soil sample locations used in this study. At the two main sites in Finland and Denmark, the Decagon 5TE and ThetaProbe responses were studied in detail. Additionally, some samples used for ThetaProbe analysis were collected in Scotland and Siberia. The soil samples used for calibration and their characteristics are listed in Table 1. According to humus form classifications (Broll et al., 2006; Zanella et al., 2011), a layer is considered organic if the soil organic matter (SOM) content is greater than ~ 30–35 %. Classification of the organic samples was undertaken according to the European Humus Forms Reference Base (Zanella et al., 2011) applying a simplified three-level scheme (water regime, form, and biotype). An overview of the classified samples is shown in Table 2, which indicates that the substrates used cover a wide range of different humus types typically encountered in the higher northern latitudes.

Soil dry bulk densities range from 0.05–0.4 and 1.0–1.5 $g\,cm^{-3}$ for the organic and mineral samples, respectively, and sand is the largest textural fraction (exceeding 80 %) in the studied mineral soils. Decagon 5TE electrical conductivity measurements of all sites remain low with values in the range between 0.00 and 0.13 $dS\,m^{-1}$.

In the following, the different sites including the collected samples and data for laboratory and field calibrations as well as validation of the derived calibration fit functions, are described in detail.

2.1 Arctic Research Center, Sodankylä, Finland (FMI)

The Finnish Meteorological Institute's Arctic Research Centre (FMI-ARC) is situated in Sodankylä (67.368° N, 26.633° E) in the boreal forest of Northern Finland intermixed with heathland, bogs, and open water (e.g. Rautiainen et al., 2012; Ikonen et al., 2015). Towards the north the forest gives way to tundra where the three latter surface types dominate. The prevailing soil type in aereated zones is podsol of mainly very sandy texture and overlying organic surface layers. A soil moisture and soil temperature network (Ikonen et al., 2015) is distributed in different land cover and soil types around the Sodankylä Research Center. At the 6 stations installed in 2011/12, Decagon 5TE Sensors were placed at 5, 10, 20, 40, and 80 cm depths, whereby the top layers (5 and 10 cm depth) hold three sensors each. Recently, two new stations were added using another soil moisture sensor type, whose calibration is planned for the near future.

2.1.1 Laboratory calibration samples

In the vicinity of two contrasting network stations samples were collected for laboratory calibration (Sect. 4.1): at station "UG Forest 1" one sample was taken from the organic surface layer ("FMI_Forest_O_L", 0–5 cm depth) along with one sample from the underlying sandy A-horizon at 10–15 cm depth ("FMI_Forest_M_L"). At station "HA Open 1", situated on heathland within a forest clearing, a pronounced organic surface layer is missing. There, samples were excavated from the sandy A-horizon at 0–5 cm ("FMI_Heath_M1_L") and 10–15 cm depth ("FMI_Heath_M2_L"), respectively.

2.1.2 Validation data

During summer 2012, a ThetaProbe measurement campaign took place around the same two network stations in order to assess soil moisture spatial variability. On 20 days hand-held measurements were taken from the surface in 1 m × 1 m grid cells inside a 30 m × 30 m area. While a certain number of grid cells was randomly chosen on each

campaign day, the three grid cells closest to the three Decagon 5TE sensors at 0–5 cm depth were always sampled, with 5 repetitions per cell. This dataset did not take part in the calibration process and thus was used for the validation of the derived calibration fit functions (Sects. 4.3 and 5.4).

2.2 Gludsted Plantation, Denmark (HOBE)

The Danish site is situated in the Skjern River Catchment in Western Denmark and has been intensely investigated in the framework of the Danish Center for Hydrology HOBE (Jensen and Illangasekare, 2011). Soil samples were collected within the Gludsted spruce plantation (56.074° N, 9.334° E) in forested parts as well as heathland. The naturally occurring soil type is a podsol of coarse sandy texture with pronounced organic surface layers. A soil moisture and soil temperature measurement station, part of a spatially distributed network (Bircher et al., 2012a) spanning a subcatchment (~ 40 km × 40 km), is installed in the forest with Decagon 5TE sensors at 5, 25, and 55 cm depths of the mineral soil as well as in the organic surface layer. Recently, further stations using the same set-up were dispersed within the plantation covering the footprint of a Cosmic-ray neutron detector (~ 600 m × 600 m, Andreasen et al., 2015).

2.2.1 Laboratory calibration samples

For laboratory calibration (Sect. 4.1), two samples, "HOBE_Forest_O1_L" and "HOBE_Forest_O2_L", were taken from organic surface layers (0–5 cm depth) in the vicinity of two forest network stations. Additionally, at the location where "HOBE_Forest_O1_L" was extracted, a mineral sample was collected ("HOBE_Forest_M_L", 10–15 cm depth).

2.2.2 Field calibration data

At the location where the sample "HOBE_Forest_O1_L" was taken, a field calibration experiment (Sect. 4.2) took place. The resulting data series "HOBE_Forest_O_F" include some additional Decagon 5TE-ThetaProbe-gravimetric sample couples available from the organic surface layers around other Decagon forest stations within the Danish Gludsted Plantation, taken in the scope of the Cosmic-ray neutron detector calibration.

In order to further increase the number of field calibration points some measurements acquired during an L-band radiometer and off-ground multi-frequency GPR campaign in 2013 (Jonard et al., 2014) were added to the database. A large soil patch from a heathland within the Gludsted Plantation was transported to the Research Center Jülich, Germany, and reinstalled below the radiometer tower using a controlled setup. The here considered soil moisture data originate from the organic surface layer (“HOBE_Heath_O_F”, 0–5 cm depth) as well as the underlying sandy A-horizon (“HOBE_Heath_M_F”, 10–15 cm depth) measured during this campaign by means of Decagon 5TE sensors, ThetaProbes, and gravimetric samples.

2.3 Additional organic samples

In Fall 2013, the Centre d’Etudes Spatiales de la Biosphère (CESBIO), Toulouse, collected two peat samples in neighboring bogs (“ISL_O_L”) on the Island Islay in Western Scotland (55.743° N, 6.178° W). Additionally, the Laboratoire d’Etudes en Géophysique et Océanographie Spatiales (LEGOS), Toulouse, provided organic samples taken on the West Siberian Plain during their field campaigns from a tundra area in Summer 2012 (65.910° N, 74.659° E) and a bog in Summer 2013 (56.941° N 82.607° E), labelled “SIB_O_L”.

3 Soil moisture sensors

3.1 Decagon ECH2O 5TE

The Decagon ECH2O 5TE sensor is based on the capacitance method to measure the medium around three 5.2 cm long prongs at 70 MHz frequency (Decagon Devices Inc., 2014). The plastic-coated sensor head is sensitive to the surrounding permittivity

and thus, should be completely covered by the medium. When using a Decagon Em50 digital/analog data logger ε_a can be estimated dividing the raw sensor output by 50. By default, the Topp equation for mineral soils (Topp et al., 1980) is used to calculate soil moisture. Besides, the probe also provides temperature and electrical conductivity measurements. The Decagon 5TE sensor as well as its predecessor TE have been tested in several studies (e.g. Kizito et al., 2008; Saito et al., 2009; Assouline et al., 2010; Rosenbaum et al., 2010 and 2011; Sakaki et al., 2011; Varble and Chavez, 2011; Ganjegunte et al., 2012; Vaz et al., 2013). To our knowledge only one calibration curve for organic material has previously been reported. However, this function by Vaz et al. (2013) is based on a sample from an artificial organic plant potting mix and was never tested in organic material from a natural soil horizon. It was only calibrated up to a water content of $\sim 0.35\,\mathrm{m^3\,m^{-3}}$ and without burying the sensor head in the material.

Some of the probe’s characteristics are listed in Table 3 including information from the manufacturer manual as well as findings by Vaz et al. (2013). Soil moisture accuracy in mineral soils is around 0.03–0.04 $\mathrm{cm^3\,cm^{-3}}$ (applying the Topp equation), and the diameter of the probe’s sensitivity lies in the range of approximately 4–8 cm. In the framework of HOBE, the Decagon 5TE sensor has been previously evaluated for near-surface sandy soil layers in the Skjern River Catchment. Using Topp’s equation, both, Vasquez and Thomsen (2010) and Bircher et al. (2012a) independently found the sensor to be accurate within ±0.02–0.03 $\mathrm{cm^3\,cm^{-3}}$ under coniferous forest, heathland, as well as in agricultural fields.

3.2 Delta-T ThetaProbe ML2x

The Delta-T ThetaProbe ML2x is a soil moisture sensor with four 6 cm long steel rods building an array whose impedance varies with the moisture content of the measured medium (Delta-T Devices Ltd., 1999). The corresponding voltage output V at 100 MHz can be converted into the soil’s apparent relative permittivity, using $\sqrt{\varepsilon_a} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3$ (Gaskin and Miller, 1996). ε_a can then be related to moisture content using the manufacturer’s calibrations for mineral and organic substrates. The probe has been evaluated in different studies and calibration functions are already reported for a range of natural organic substrates (e.g. Kurum et al., 2012; Overduin et al., 2005; Yoshikawa et al., 2004), and artificial potting/compost substrates (e.g. Nemali et al., 2007; Kargas and Kerkides, 2008; Kang et al., 2010; Vaz et al., 2013). Major probe characteristics are listed in Table 3. Soil moisture accuracy in mineral soils is around 0.03–0.05 $cm^3 cm^{-3}$ (applying factory-supplied calibration), and the diameter of the probe's sensitivity lies in the range of approximately 2–4 cm.

4 Method

4.1 Laboratory calibration measurements

Laboratory sensor calibrations for the organic and mineral substrates collected in Finland and Denmark (specified in Sects. 2.1.1 and 2.2.1) were carried out at the respective institutions, following the same protocol. As organic material can be strongly affected by shrinkage during drying (e.g. Schaap et al., 1996; Pumpanen and Ilvesniemi, 2005), a significant error might occur when assuming a constant bulk density over the entire water content range. To avoid this issue the material was initially saturated and was then allowed to undergo a dry down to account for the changing volume. The saturated bulk densities of the respective soils were previously estimated from field samples and the collected saturated material was packed accordingly into large buckets. In the center of each bucket one Decagon 5TE sensor was installed permanently at the surface and in a horizontal fashion with the blade in vertical direction, in order to avoid ponding of water on the sensor. Distances to the bucket borders were clearly larger than the maximum diameter of the probe's sensitivity (Table 3). The Decagon 5TE readings were logged continuously, while ThetaProbe measurements and gravimetric samples were taken from the surface at defined times. The ThetaProbe was pushed firmly into the substrate in order to assure good contact and avoid air gaps. A mean of three readings was recorded each time, while one reference sample was

extracted using steel rings of known volume. As buckets were of large sizes enough material for all the gravimetric samples was available without disturbing the sensor measurements and no backfilling of material was necessary. The samples were oven-dried at 105 °C during 24 h for the mineral soils and at 85 °C during 48 h for the organic material as practiced by Nagare et al. (2011). O'Kelly (2004) had found that around this temperature mass loss due to charring balanced the effects of residual water caused by the strong water binding capacities of organic matter. Subsequently, the estimated gravimetric moisture contents were converted into volumetric moisture contents by the knowledge of the bulk density. Soil texture and organic carbon were determined using standard procedures (sieving as well as Malvern Mastersizer 2000 and loss on ignition).

The samples from organic surface horizons in Siberia and Scotland (Sect. 2.3) were handled at CESBIO, France. They were not large enough to place Decagon 5TE sensors. Thus, only ThetaProbe readings (in triplicates) and respective gravimetric samples were taken.

4.2 Field calibration measurements

During the field calibration experiment in the vicinity of one Danish forest network station (see Sect. 2.2.2), a Decagon 5TE sensor was installed in the organic horizon and logged continuously. After the first measurements of extremely dry conditions in summer 2013, the soil was saturated. During the dry down three ThetaProbe readings and gravimetric samples were acquired and averaged for each measurement in time. In case of these data and all additional field observations used in this study (Decagon 5TE – ThetaProbe – Gravimetric sample couples described in Sect. 2.2.2), sensor installation, measurement and drying protocols were identical to the ones described above for the laboratory calibration.

4.3 Fitting of calibration functions and validation

All field and laboratory data were gathered and sensor output was plotted against volumetric moisture content for Decagon 5TE/ThetaProbe and organic/mineral samples, respectively. In case of continuously logged Decagon 5TE data, the two measurements closest to each ThetaProbe/sample timestamp were extracted and averaged. The number of available points per site and sensor type is indicated in Table 1. Sensor calibrations based on our measurements were carried out for the ensemble of data measured in the organic horizons of all studied sites, while for the data from underlying mineral soil layers the validity of the manufacturer calibrations was tested. Calibration curves were fitted through the data using mathematical descriptions already reported in literature on soil moisture sensor calibration. For Decagon 5TE data pairs of apparent relative permittivity readings vs. volumetric moisture contents this included 3rd order polynomial, power, natural logarithm, and square root functions. With respect to the ThetaProbe, fit functions were derived for both, output voltage-volumetric moisture and apparent relative permittivity-volumetric moisture pairs, (3rd and 1st order polynomial, respectively) as they are equally used in many studies. The fitted functions were compared with corresponding manufacturer calibration curves as well as calibrations reported in literature (specified in Sect. 5.3).

To further validate the proposed fit functions, Decagon 5TE and ThetaProbe soil moisture time series from two Sodankylä network stations recorded during summer 2012 and not used in the calibration process (see Sect. 2.1.2) were compared to test whether the soil moisture from the two sensor types agreed. At both, the "UG Forest 1" and "HA Open 1" sites, one of the three Decagon 5TE sensors at 5 cm depth was chosen for the exercise together with the immediately adjacent ThetaProbe surface data, whose 5 readings per day were averaged. In case of the Decagon 5TE data the mean of the two closest time steps around average ThetaProbe acquisition time was taken, resulting in maximum time shift between the two measurements of less than 30 min. For the organic surface layer at the "UG Forest 1" site soil moisture estimates using

manufacturer default calibrations as well as newly derived fit functions were compared. Thereby, the ThetaProbe "organic" default function was chosen, while for the Decagon 5TE sensor the only available Topp et al. (1980) equation for mineral soils was applied. For the low organic mineral surface soil at the "HA Open 1" site default functions for mineral soils provided by the manufacturers were considered. To get a better insight into the temporal evolution of the soil moisture pattern over time, hourly rainfall intensities (R_1H) measured at Tähtelä at the center of the Sodankylä research area ($\sim$ 0.5 and 2.5 km distance from the "HA Open 1" and "UG Forest 1" network stations) were plotted along.

For the statistical analysis throughout our study the Pearson's correlation coefficient (R), bias (mean difference between excepted and measured values), and bias-corrected Root Mean Square Deviation (RMSD) were computed.

5 Results and discussion

5.1 Sensor output – volumetric moisture content response

Figure 2 depicts the Decagon 5TE and ThetaProbe output (ε_a and voltage, respectively) separately plotted against the volumetric moisture content for the studied organic (> 30 % SOM) and mineral soil horizons (< 30 % SOM). The corresponding manufacturer calibration curves are depicted as well. Additionally, points were color coded to distinguish between SOM contents (see Table 1 for SOM contents of the respective samples), while data obtained from laboratory and field measurements are discriminated by different symbol types.

Despite the scatter in the data measured in organic layers a clear trend is detectable irrespectively of the sample location or humus type. Furthermore, for both sensor types, the field measurements under less disturbed conditions are also in good agreement with the laboratory data.

For the mineral soils with a SOM content below 10 % both Decagon 5TE and ThetaProbe data scatter around the respective manufacturer calibration curves, and thus, demonstrate the validity of the latter. In case of the Decagon 5TE sensor this underlines earlier results by Vasquez and Thomsen (2010) and Bircher et al. (2012a) who also found the sensor to be accurate within ±0.02–0.03 $cm^3\,cm^{-3}$ in sandy A-horizons with low organic matter contents using default Topp's equation.

In contrast, for the mineral samples with a SOM exceeding 10 % the trends in the data differ for both sensor types. While for the ThetaProbe the data of increased SOM content show a behavior comparable to the measurements in mineral soils with SOM < 10 %, in the respective Decagon 5TE data a clear tendency towards a decrease in apparent relative permittivities at given moisture contents can be observed. For the measurements in the organic horizons (> 30 % SOM), this trend of decreasing ε_a for a given moisture content with increasing SOM content is even more distinct. Especially at higher moisture contents a more or less constant offset is detectable, while below $\sim 0.4\,cm^3\,cm^{-3}$ an increase in curvature is observable, indicating only a small change in ε_a for a relatively large change in soil moisture. This behavior is in good agreement with observations from TDR readings (e.g. Topp et al., 1980; Roth et al., 1992; Paquet et al., 1993; Kellner and Lundin, 2001; Jones et al., 2002), and can be explained by the substantial fraction of bound water on the large surface area of the organic material. Considerable amounts of rotationally hindered water molecules result in the recording of lower apparent relative permittivities for organic-rich materials compared to mineral soils for the same water content. Adsorption forces decrease exponentially with increasing distance to the solid surface. At low water contents where first layers affected by binding forces closest to solid surfaces are filled, an increase in moisture content barely increases ε_a. Once these layers are filled, a further increase in moisture level results in a more rapid rise of ε_a. Hence, the offset compared to the sensor response in mineral soils of low SOM content becomes constant. The value of 10 % SOM as threshold for the appearance of bound water effects is in accordance with findings reported by Paquet et al. (1993), Vaz et al. (2013), and Vasquez (2013). Hence, these

data suggest that if more such Decagon 5TE readings were collected in the future, an attempt could be made to derive a calibration law for mineral horizons as function of SOM content. In purely organic horizons bound water effects are most pronounced, whereby, above 30 % SOM content the dependency of the magnitude of bound water effects on the SOM content seems to level off, meaning that no further decrease of ε_a with augmenting soil organic matter is clearly detectable.

In contrast, the ThetaProbe data for the organic soil layers show a closer match between our soil moisture measurements and soil moisture computed based on the default calibrations for mineral and organic substrates. It is worthwhile noting that there is only a small difference in the soil moisture estimation between the two default calibration curves whilst their shape remains consistent. Nevertheless, in the medium to high range of the sensor outputs (600–1000 mV) for the organic samples the default curves are not able to reproduce our measurements due to more pronounced curvature in our data. This results in (1) a tendency towards increased sensor output at a given moisture content compared to both default curves in the middle range, and (2) saturation in the sensor's response around 1000 mV.

In conclusion, one can state that for both sensor types deviating sensor outputs in case of measurements conducted in organic horizons compared to mineral layers with low SOM content are clearly demonstrated. The scatter in the data from organic horizons is in comparable range as reported for similar calibration studies using TDR sensors (e.g. Schaap et al., 1996; Kellner and Lundin, 2001; Pumpanen and Ilvesniemi, 2005; Nagare et al., 2011). Thereby, the spread is always higher for organic substrates compared to mineral soils due to the complex nature of the former. However, no distinct differences in measurements' behavior from samples ranging a variety of humus types and acquired by different users are noticeable. Based on this first analysis it can be hypothesized that for each sensor type one calibration function should hold for reliable estimates of the moisture content in organic surface horizons (> 30 % SOM) of different characteristics and variable SOM. In the following, the presented results and discussion will concentrate on this subject.

5.2 Curve fits for organic material

Figure 3 illustrates the calibration curves fitted through the data measured in the different organic soil layers. For the Decagon 5TE sensor different functions (3rd order polynomial, power, natural logarithm and square root functions) were tested. In case of the ThetaProbe, fit functions were derived based on 1st and 3rd order polynomial functions for ε_a and output voltage to volumetric moisture content, respectively. For comparison, manufacturer calibration curves are als included in the plots. All functions shown in Fig. 3 are listed in Table 4 and the corresponding fitting statistics are presented in Table 5.

For the Decagon 5TE sensor, the statistics show no clear difference between the different tested fit functions. Compared to the manufacturer calibration all of them result in a significantly decreased bias and an improved RMSD while R remains unchanged. Based on a visual inspection the natural logarithmic fit seems to most closely follow the measured data with a more pronounced curvature at low moisture contents up to about 0.2 $cm^3\,cm^{-3}$, and a similar curvature as the mineral default function for higher moisture contents.

For the ThetaProbe the 3rd order polynomial fit between the sensors millivolt (mV) output and the measured soil moisture shows a similar curve shape as the default functions for mineral and organic substrates, but with the aforementioned increased curvature. Meanwhile, a steeper slope compared to the quasi linear default curves becomes apparent in case of the 1st order polynomial fit through the ε_a-moisture content couples. For both new functions (mV-moisture content and ε_a-moisture content), the R and RMSD improved slightly, whereas the bias stayed in the order of the default function for mineral soils, which is clearly lower than for the default function for organic materials.

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5.3 Comparison of fitted vs. literature calibrations for organic materials

Figure 4 displays the functions fitted to our organic samples (only the selected logarithmic function for Decagon 5TE) together with petrophysical or empirical relationships for organic samples taken from literature. In case of the Decagon 5TE sensor this includes the calibration for an organic plant potting mix reported by Vaz et al. (2013) for the same sensor type as well as the following calibration laws for organic samples obtained from TDR measurements: Pepin et al. (1992), Roth et al. (1992), Paquet et al. (1993), Malicki et al. (1996) using a bulk density of 0.1 $g\,cm^{-3}$, Schaap et al. (1996), Kellner and Lundin (2001), Yoshikawa et al. (2004) for living sphagnum, and Pumpanen and Ilvesniemi (2005). Concerning the ThetaProbe, only functions derived for organic soil layers with the same sensor type were selected, namely those of Nemali et al. (2007), Kurum et al. (2012) for an OL layer using a bulk density of 0.1 $g\,cm^{-3}$, and Vaz et al. (2013) for the relationship between mV output and moisture content (plotted in the upper right panel), and Yoshikawa et al. (2004, living sphagnum) as well as Kargas and Kerkides (2008) for the relationship between ε_a and moisture content (plotted in the lower right panel), respectively. Corresponding statistics are listed in Table 6.

The natural log fit and the calibration proposed by Vaz et al. (2013) applied to our data exhibit a similar R value, while both RMSD and bias increased for the latter. The two curves follow each other closely within the calibration range of Vaz et al. (2013), while they deviate beyond a water content of $\sim 0.5\,cm^3\,cm^{-3}$ due to a more pronounced curvature of our natural log fit. Good agreement within the calibrated range of two curves derived from different natural organic horizons and a plant potting mix further strengthens confidence that the type and structure of organic material does not drastically affect the measurements themselves. And the same seems to account for the application with or without burying the sensor head in the materials, as practiced in this work and by Vaz et al. (2013), respectively. This adds a further point of validity, making the here derived function even more generally applicable.

For the functions derived from TDR measurements in organic soil layers R values also stayed in the same order as for our fitted functions. Compared to our best suited function (natural log fit) the ones proposed by Paquet et al. (1993), Schaap et al. (1996), Kellner and Lundin (2001), and Malicki et al. (1996) using a bulk density of 0.1 $cm^3\,cm^{-3}$ (curves in blue colors), lie in the same range with very similar RMSD, and small (though some order of magnitudes larger) bias of around ±0.01 $cm^3\,cm^{-3}$. Furthermore, the curvatures of these functions are slightly less pronounced either in the dry or wet range. Other functions (curves in green colors) are clearly offset with mostly larger RMSD, significantly larger bias (above 0.03 $cm^3\,cm^{-3}$) and less curvature (Pepin et al., 1992; Roth et al., 1992; Yoshikawa et al., 2004; Pumpanen and Ilvesniemi, 2005). While the absolute match between the calibration curves for organic material of the Decagon 5TE sensor and the TDR based ones is not always good, it is still worthwhile noting that they all show the same general curve shape. The discrepancies between these different calibration laws presumably arise from the different sensor designs, measurement principles, and measurement frequencies used as also pointed out by Vaz et al. (2013).

For the ThetaProbe mV vs. moisture content relationship all considered calibrations show very similar behavior as the default calibrations up to ~ 0.2 $cm^3\,cm^{-3}$. However, at higher moisture contents the curves start deviating significantly without a clear pattern. Like our 3rd order polynomial fit the function reported by Vaz et al. (2013) exhibits the same type of shape as the default functions though with weaker curvature. Meanwhile, the Nemali et al. (2007) and Kurum et al. (2012) functions show differing characteristics. In any case, the statistics in terms of all measures clearly deteriorate when applying other calibration laws to our data. The Nemali et al. (2007) curve and our fit function were calibrated even for high moisture contents (0.8–0.9 $cm^3\,cm^{-3}$), while the Vaz et al. (2013) and Kurum et al. (2012) fits were derived only for low to moderate moisture contents up to 0.3–0.35 $cm^3\,cm^{-3}$.

In case of the ThetaProbe ε_a vs. moisture content calibration, all included calibration laws perform similarly well in terms of R, while those of Kargas and Kerkides (2008) and Yoshikawa et al. (2004) showed increased RMSDs and biases (with opposite signs

for the two specified functions). The Kargas and Kerkides (2008) curve (calibrated up to 0.75 $cm^3\,cm^{-3}$) exhibit a shape similar to the default curves though with lower ε_a at a given moisture content. Yoshikawa et al. (2004) show a more analog trend to our data with larger ε_a for a given moisture content compared to the mineral default curve and deviation starts above 0.3 $cm^3\,cm^{-3}$ when leaving the Yoshikawa et al. (2004) calibration range.

The presented results indicate that for the ThetaProbe data a clear consistency between measurements, fitted functions, theory and literature calibrations is lacking. As practiced in our experimental setup, Nemali et al. (2007), Kurum et al. (2012), and Vaz et al. (2013) also removed and re-inserted the ThetaProbe after each measurement, while in the studies by Yoshikawa et al. (2004) and Kargas and Kerkidis (2008) probes remained installed throughout the entire experiments. Certainly, a hand-held application with slightly changed sampling location each time results in increased data variability compared to permanently installed probes, the effect being more pronounced in organic substrate of complex structure compared to more homogeneously distributed mineral soils. However, irrespectively of the two approaches used, no clear difference is detectable in the functions' curve shapes. Another plausible explanation for the nonuniform behavior could be the ThetaProbe's rod configuration that significantly concentrates the electromagnetic field around the central electrode, resulting in a small sampling volume (Table 3). This drawback was already raised by Robinson et al. (1999) and Vaz et al. (2013) who stated that this possibly renders the measurements more sensitive to compaction during the insertion of the instrument as the effect is most distinct around the probe's center. Additionally, this problem becomes more important as moisture content increases. This would clarify why the agreement between different calibration curves is best at very small water contents and deteriorates more and more towards high soil moisture values.

5.4 Comparison of soil moisture time series at two Sodankylä network sites

Figure 5 shows the comparison of average Theta Probe and Decagon 5TE soil moisture estimates collected in Sodankylä during summer 2012. Time series and scatter plots of soil moisture measured in 0–5 cm depth from the "HA Open 1" network station with low organic mineral soil as well as at the "UG Forest 1" network station with a pronounced organic surface layer are depicted. For the ThetaProbe average of 5 readings respective standard deviations are displayed in form of errorbars. Hourly rainfall intensities (R_1H) are also plotted along. Details on the applied calibration functions as well as corresponding statistics are given in Table 7.

The measurements of the two sensor types at the "HA Open 1" site are in very good agreement using the default calibrations for mineral soils. In contrast, applying the most appropriate default calibrations available for the two sensors at the "UG Forest 1" site, a pronounced difference in soil moisture content is detectable. Thereby the ThetaProbe soil moisture estimates are much wetter and their range much larger compared to the Decagon 5TE sensor. When using our fit functions derived for organic material (3rd order polynomial for ThetaProbe and natural logarithm for Decagon 5TE), the agreement becomes much better with significantly decreased RMSD and bias. Also, it now nicely stands out that the mean soil moisture level of the sandy mineral soil is lower but with larger temporal dynamics compared to the organic surface layer. This behavior is expected due to low and high water retention capacities of the two materials, respectively.

Only the correlation between the two sensors remains still low in case of the organic layer, especially caused by the observed scatter in the ThetaProbe data obtained by a hand-held application with constantly changed sensor locations. This scatter is in similar range with the data variability presented by Kurum et al. (2012), and significantly larger than observed in the mineral soil, both in terms of daily standard deviations of the 5 probe readings (errorbars) and day to day variations. As already discussed in Sect. 5.3, the more pronounced short range variabilities in the organic substrate

are a consequence of more complex structure compared to the more homogeneously distributed sandy soil encountered at the "HA Open 1" site, possibly intensified by compaction effects originating from the suceptible sensor. However, irrespectively the cause, the newly derived fit functions clearly outperform the default calibration functions at the "UG Forest 1" site.

We suggest that these new ThetaProbe calibrations for organic substrates should only be used for the probe application method they were derived from, i.e. hand-held. In that case, even if soil moisture data acquired using the ThetaProbe in organic-rich soils should be interpreted carefully, the sensor used together with the here proposed calibration functions proofs robust and of value for the acquisition of quick and instantaneous information about the moisture content for large areas, as for example practiced in airborne campaigns for satellite Cal/Val purposes (e.g. Cosh et al., 2005, Bircher et al., 2012b). There, averaging over larger sets of readings will further balance out differing compaction and heterogeneity effects in individual readings – compared to our example where the mean of only 5 ThetaProbe readings was taken for comparison with point station data.

Finally, comparison with hourly rainfall intensities shows that the Decagon 5TE soil moisture time series estimated using the newly developed calibration function also well reflect the precipitation pattern, demonstrating the sensor's ability to yield reliable soil moisture time series in both mineral and organic substrates. Based on the very satisfying overall performance of the derived natural log fit function, it was applied in the calculation of the Decagon 5TE network soil moisture from organic surface layers at the Sodankylä and HOBE study sites to improve the quality in the so far gathered data.

6 Summary and conclusions

At both, the Finnish Meteorological Institute's Arctic Research Center (FMI-ARC) in Sodankylä and the study site of the Danish Center for Hydrology HOBE, soil moisture is a key research topic. With the purpose of serving coarse resolution satellite remote sensing and land surface modeling studies, Decagon 5TE sensors are applied in permanent soil moisture networks while ThetaProbes are used for hand-held soil moisture measurement campaigns. Because both locations are characterized by organic-rich soils, a joined effort aimed at calibrating these two electromagnetic sensor types for organic surface layers with SOM contents above 30 %. While some ThetaProbe calibration efforts for organic soil horizons are present in literature, for the Decagon 5TE sensor such a calibration function has only been reported for an artificial organic material measured throughout a limited water content range (Vaz et al., 2013). The objective of the here presented study was to provide generic and widely applicable calibrations for both studied sensor types holding for a variety of natural organic substrates as encountered within the large areas under consideration. Necessarily these functions hold a decreased degree of detail and might lack high accuracy, but will clearly outperform standard calibration functions reported by the manufacturers. The used soil samples originated from different locations in northern regions, mainly including the Sodankylä and HOBE network areas, spanning a wide range of different humus types. We believe that a reliable calibration approach has been worked out with (1) the same measurement and calibration protocol followed at all sites, (2) comparison of data from organic and mineral horizons including laboratory and field measurements, and (3) consideration of material-specific characteristics such as shrinkage and charring during drying.

For both, the Decagon 5TE sensor and the ThetaProbe, the variety of organic samples showed a consistent sensor output-moisture content response. Likewise, this was the case when the laboratory experiment was repeated in the field under less disturbed conditions, demonstrating independence of the acquired data from the chosen experimental setup. Deviating sensor outputs for measurements conducted in organic horizons (> 30 % SOM) compared to mineral layers were clearly identified (see Table 1 for SOM contents). For the mineral soil layers with a soil organic matter content below 10 % the validity of the respective manufacturer calibrations could be demonstrated in case of both Decagon 5TE and ThetaProbe. For the mineral samples with a SOM con-

tent exceeding 10 % the ThetaProbe data showed a behavior comparable to the measurements in mineral soils with SOM fraction < 10 %, while in the respective Decagon 5TE data a clear tendency towards decreased ε_a at a given moisture content could be observed. This effect became even more pronounced for the measurements in the organic horizons though it seemed to level off, meaning that beyond a SOM content of 30 % no further ε_a decrease with augmenting soil organic matter was clearly visible. This behavior is in accordance with previous TDR studies (e.g. Topp et al., 1980; Roth et al., 1992; Paquet et al., 1993; Kellner and Lundin, 2001; Jones et al., 2002), and explicable by an increased bound water fraction in porous organic matter with a high surface area fraction compared to the underlying sandy mineral soils. In contrast, the ThetaProbe data acquired from the organic soil layers showed a closer match with the manufacturer's mineral and organic functions, though with more pronounced curvature.

Based on the above results, for all data measured in the organic horizons one calibration function was derived per sensor type. A natural logarithm and 1st order polynomial were fitted through the ε_a and soil moisture couples for the Decagon 5TE and ThetaProbe sensors, respectively. In case of the ThetaProbe, a 3rd order polynomial was selected for the corresponding pairs of voltage and soil moisture.

The fact that there was no clear difference in the data obtained from the different sampling sites spanning a variety of humus types and acquired by different users strengthens confidence that the derived calibration functions are not only site specific but can be applied over a wide range of locations and organic materials of differing characteristics and SOM contents. This renders them highly suitable to support large-scale remote sensing and land surface modeling studies.

In case of the Decagon 5TE sensor the reliability of the proposed calibration function is further underlined by the fact that it obeys the theory of increased bound water fraction for organic material, the good agreement with the Decagon 5TE calibration law for a plant potting mix reported by Vaz et al. (2013), as well as by comparable curve shapes as presented in respective TDR calibration studies. Meanwhile, for the ThetaProbe data such a clear consistency between measurements, fitted functions, and theory is lacking, which is further reflected in the nonuniform behavior of earlier derived calibration laws for organic material reported by other authors.

Comparison of independent Decagon 5TE and ThetaProbe soil moisture time series using default calibrations (not used for the calibration) yield good agreement for the Sodankylä "HA Open 1" network stations' mineral surface layer. In case of the "UG Forest 1" network stations' organic surface horizon reasonable accordance could only be achieved when using our fit functions derived for organic material (natural logarithm for Decagon 5TE and 3rd order polynomial for ThetaProbe). The latter significantly improved RMSD and bias so that average soil moisture levels coincided. Only the correlation between the two sensors in the organic layer stayed low, especially caused by the observed scatter in the ThetaProbe data. This is mostly a consequence of the hand-held application with constantly changed sensor locations, leading to more pronounced short range variabilities in the data from a highly heterogeneous material, possibly intensified by compaction effects originating from the susceptible sensor. However, irrespectively the cause, the newly derived calibration fit functions clearly outperform the default functions at the "UG Forest 1" site.

We suggest that the newly derived ThetaProbe calibration fit functions for organic substrates should only be used together with the probe application it was derived from, i.e. hand-held. In that case, the functions proof robust and of value for the acquisition of quick and instantaneous information about the moisture content for large areas, where averaging over larger sets of readings will balance out differing compaction and heterogeneity effects in individiual readings.

Finally, field data from Sodankylä demonstrate the ability of the Decagon 5TE sensor to reflect precipitation patterns in mineral soils as well as organic horizons. Based on the very satisfying overall performance of the derived natural log fit function it was applied in the calculation of soil moisture from organic surface layers at the Sodankylä and HOBE network sites to improve the quality in the so far gathered data.

Though the here proposed calibration functions are derived based on samples collected in the higher Northern latitudes, they should also be applicable to soil moisture

measurements in similar media encountered in other regions of the world. If more data were collected in the future, a Decagon 5TE calibration law for mineral horizons as function of SOM content could possibly be derived.

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Table 1. Overview of the samples used for calibration. The sample name starts with the study site, followed by land cover type, soil material and indication whether used in laboratory or field calibration. O, M, F, and L denote organic, mineral, field and lab, respectively. The letter specifying the soil material is complemented by a number if more than one sample of the same soil material is available at a given study site. N = Number of sensor measurements.

Soil material	Sample name	Location	Land cover	Method	Layer depth [cm]	SOM [%]	Sand/silt/ clay [%]	N Decagon 5TE	N ThetaProbe
Organic	HOBE_Forest_O_F	Gludsted, DK	Forest	Field	0–5	69–93.0	NaN	19	13
	HOBE_Forest_O1_L	Gludsted, DK	Forest	Lab	0–5	69.0	23.1/7.8/0.1	11	11
	HOBE_Forest_O2_L	Gludsted, DK	Forest	Lab	0–5	31.0	66.1/3.3/0.0	11	11
	HOBE_Heath_O_F	Gludsted, DK	Heath	Field	0–5	NaN	NaN	2	8
	FMI_Forest_O_L	Sodankylä, FI	Forest	Lab	0–5	36.6	61.7/1.4/0.3	7	7
	SIB_O_L	Siberia, RU	Tundra/bog	Lab	0–5	NaN	NaN	0	3
	ISL_O_L	Islay, GB	Bog	Lab	0–5	NaN	NaN	0	17
Mineral	HOBE_Forest_M_L	Gludsted, DK	Forest	Lab	10–15	8.0	83.9/7.6/0.3	11	11
	HOBE_Heath_M_F	Gludsted, DK	Heath	Field	10–15	15.8	84.7/13.9/1.4	4	7
	FMI_Forest_M_L	Sodankylä, FI	Forest	Lab	10–15	15.1	84.8/0.2/0.0	6	6
	FMI_Heath_M1_L	Sodankylä, FI	Heath	Lab	0–5	6.9	91.5/1.4/0.3	5	5
	FMI_Heath_M2_L	Sodankylä, FI	Heath	Lab	10–15	5.0	92.4/2.6/0.0	4	4

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Table 2. Overview over organic samples, classified according to the European Humus Forms Reference Base (Zanella et al., 2011).

Location	Land cover	Water regime	Form	Biotype	Horizons	Decagon 5TE	ThetaProbe
Gludsted, Denmark	Coniferous forest	Terrestrial	Terro	Mor	OL-OF-OH	x	x
	Heathland	Terrestrial	Terro	Moder	OL-OH	x	x
Sodankylä, Finland	Coniferous forest	Terrestrial	Terro	Mor	OL-OF-OH	x	x
	Heathland	Terrestrial	Enti	Mor	OL-OF-OH	x	x
West Siberia, Russia	Tundra	Semi-terrestrial	Hydro	Hydromor	(OLg)-OFg-(OHg)	–	x
	Bog	Semi-terrestrial	Histo	Histomor	hf	–	x
Islay, Scotland, GB	Bog	Semi-terrestrial	Histo	Histomor	hf-hm	–	x

Table 3. Soil moisture sensor characteristics from manufacturer manuals as well as findings of Vaz et al. (2013).

Sensor	Type	Frequency [MHz]	Output type	Lenght of prongs [cm]	Sampling diameter (of influence) [cm]		Soil moisture accuracy (factory calibration mineral) [$cm^3\,cm^{-3}$]	
					Manufacturer	Vaz et al. (2013)	Manufacturer	Vaz et al. (2013)
Decagon ECH2O 5TE	Capacitance	70	Raw (= $50\varepsilon_a$)	5.2	8.6	4.4	0.030 Topp et al. (1980)	0.040
Delta-T ThetaProbe ML2x	Impedance	100	Voltage	6.0	4.0	2.0	0.050	0.029

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Table 4. Manufacturer's default calibration functions and functions fitted through the data measured in organic layers (SOM > 30 %) as shown in Fig. 3 for Decagon 5TE ($\theta = \text{fct.}(\varepsilon_a)$) and Delta-T ThetaProbe ($\theta = \text{fct.}(\varepsilon_a)$ and $\theta = \text{fct.(voltage)}$), respectively. θ = volumetric moisture content, ε_a = apparent relative permittivity.

Sensor type	$\theta = \text{fct.}(x)$	Function type	Function
Decagon ECH2O 5TE	ε_a	Default mineral	$\theta = 4.3 \times 10^{-6} \times \varepsilon_a^3 - 5.5 \times 10^{-4} \times \varepsilon_a^2 + 2.92 \times 10^{-2} \times \varepsilon_a - 5.3 \times 10^{-2}$
		Fit (3rd order polynomial)	$\theta = 6.9593 \times 10^{-6} \times \varepsilon_a^3 - 9.8511 \times 10^{-4} \times \varepsilon_a^2 + 4.5834 \times 10^{-2} \times \varepsilon_a - 5.0595 \times 10^{-2}$
		Fit (Power)	$\theta = 0.831074 \times \varepsilon_a^{0.192743} - 0.978084$
		Fit (Natural logarithm)	$\theta = 0.262621 \times \ln(\varepsilon_a) - 0.279003$
		Fit (Square root)	$\theta = 0.140543 - 0.139004 \times \sqrt{\varepsilon_a}$
Delta-T ThetaProbe ML2x	ε_a	Default mineral	$\theta = -0.190 + 0.119 \times \sqrt{\varepsilon_a}$
		Default organic	$\theta = -0.168 + 0.130 \times \sqrt{\varepsilon_a}$
		Fit (1st order polynomial)	$\theta = 1.4894 \times 10^{-2} \times \varepsilon_a - 3.2685 \times 10^{-3}$
	Voltage	Default mineral	$\theta = 0.56 \times V^3 - 0.762 \times V^2 + 0.762 \times V - 0.063$
		Default organic	$\theta = 0.61 \times V^3 - 0.831 \times V^2 + 0.831 \times V - 0.030$
		Fit (3rd order polynomial)	$\theta = 1.4964 \times 10^{-9} \times mV^3 - 2.0401 \times 10^{-6} \times mV^2 + 1.0516 \times 10^{-3} \times mV - 1.9707 \times 10^{-2}$

Table 5. Statistics for manufacturer's default calibration curves and functions fitted through the data measured in organic layers (SOM > 30 %) as listed in Table 4 for Decagon 5TE ($\theta = \text{fct.}(\varepsilon_a)$) and Delta-T ThetaProbe ($\theta = \text{fct.}(\varepsilon_a)$ and $\theta = \text{fct.(voltage)}$), respectively: N = Number of sampling points, R = Pearson's correlation coefficient, RMSD = bias-corrected root mean square deviation, BIAS = bias, θ = volumetric moisture content, ε_a = apparent relative permittivity.

Sensor type	$\theta = \text{fct.}(x)$	Function type	N	R	RMSD	BIAS
Decagon ECH2O 5TE	ε_a	Default mineral	50	0.92	0.077	0.127
		Fit (3rd order polynomial)	50	0.92	0.068	1.17×10^{-17}
		Fit (Power)	50	0.92	0.070	-4.82×10^{-16}
		Fit (Natural logarithm)	50	0.92	0.070	3.68×10^{-9}
		Fit (Square root)	50	0.91	0.071	-2.42×10^{-12}
Delta-T ThetaProbe ML2x	ε_a	Default mineral	70	0.84	0.110	−0.004
		Default organic	70	0.84	0.110	−0.080
		Fit (1st order polynomial)	70	0.87	0.102	0.004
	Voltage	Default mineral	70	0.84	0.110	−0.004
		Default organic	70	0.84	0.110	−0.078
		Fit (3rd order polynomial)	70	0.87	0.100	0.001

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Table 6. Statistics for the applied petrophysical and empirical relationships for organic soil layers extracted from literature as well as for manufacturer's default calibration curves and our best fits (as presented in Fig. 4). N = Number of sampling points, R = Pearson's correlation coefficient, RMSD = bias-corrected root mean square deviation, θ = volumetric moisture content, ε_a = apparent relative permittivity.

Sensor type	θ = fct.(x)	Sensor type original study	Source	N	R	RMSD	BIAS
Decagon ECH2O 5TE	ε_a	–	Fit (Natural logarithm)	50	0.92	0.070	3.68×10^{-9}
		Decagon ECH2O 5TE	Vaz et al. (2013)	50	0.91	0.075	0.003
		TDR	Roth et al. (1992)	50	0.91	0.072	0.084
			Yoshikawa et al. (2004) (living org.)	50	0.91	0.077	0.133
			Pepin et al. (1992)	50	0.90	0.077	0.032
			Pumpanen and Ilvesniemi (2005)	50	0.91	0.086	0.077
			Malicki et al. (1996) (bulk density = 0.1)	50	0.91	0.071	−0.013
			Kellner and Lundin (2001)	50	0.91	0.071	−0.012
			Schaap et al. (1996)	50	0.92	0.071	−0.008
			Paquet et al. (1993)	50	0.92	0.069	−0.018
Delta-T ThetaProbe ML2x	ε_a	–	Fit (1st order polynomial)	70	0.87	0.102	0.004
		Delta-T ThetaProbe ML2x	Yoshikawa et al. (2004) (living org.)	70	0.87	0.111	0.063
			Kargas and Kerkides (2008)	70	0.84	0.123	−0.169
	Voltage	–	Fit (3rd order polynomial)	70	0.87	0.100	0.001
		Delta-T ThetaProbe ML2x	Vaz et al. (2013)	70	0.81	0.124	−0.008
			Nemali et al. (2007)	70	0.70	0.154	0.045
			Kurum et al. (2012) (OL layer, bulk density = 0.1)	70	0.80	0.124	−0.129

Table 7. Statistics for comparison of 0–5 cm volumetric moisture content (θ) estimates by means of Delta-T ThetaProbe and Decagon 5TE sensors at the Sodankylä "HA Open 1" (low organic mineral soil, SOM = 6.89 %) and "UG Forest 1" (organic substrate, SOM = 36.59 %) network stations during summer 2012, using calibration functions as indicated below. N = Number of sampling points, R = Pearson's correlation coefficient, RMSD = bias-corrected root mean square deviation, and BIAS = bias.

Site	Calibration function type		N	R	RMSD	BIAS
	Delta-T ThetaProbe ML2x	Decagon ECH2O 5TE				
Sodankylä "HA Open 1"	Default mineral	Default mineral	17	0.82	0.0142	−0.0097
Sodankylä "UG Forest 1"	Default organic	Default mineral	18	0.12	0.0663	0.1566
	Fit 3rd order poly organic	Fit natural log organic	18	0.06	0.0355	−0.0238

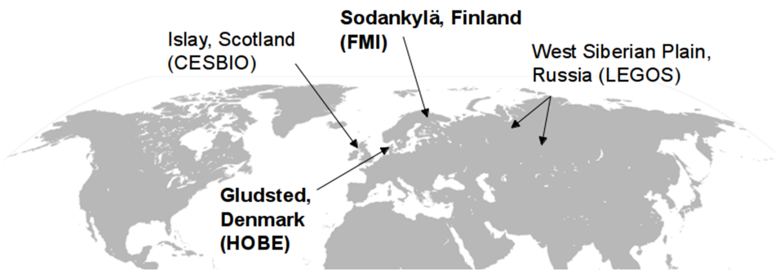

Figure 1. Overview over all sampling locations (main study sites are in bolt).

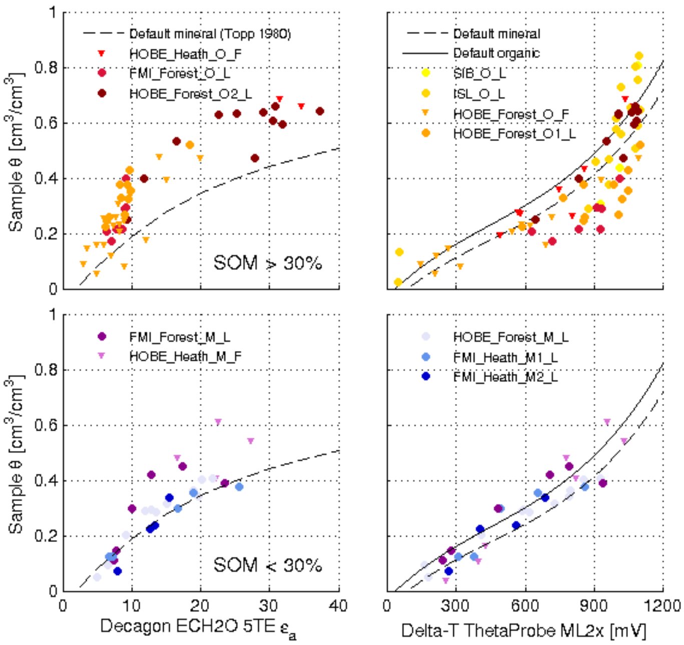

Figure 2. Decagon 5TE apparent relative permittivity ε_a (left) and ThetaProbe voltage [mV] (right column) against volumetric moisture content θ for organic (SOM > 30 %, top row) and mineral soil horizons (SOM < 30 %, bottom row), laboratory • and field ▼ data, with color codes from highest to lowest SOM content (yellow – dark red and purple – dark blue, respectively). For mineral horizons, blue and purple signatures mean SOM < 10 and > 10 %, respectively. Manufacturer's default calibration curves (black dashed and continuous lines) are also included. Regarding the specifications of sample names and respective SOM fractions, please see Table 1.

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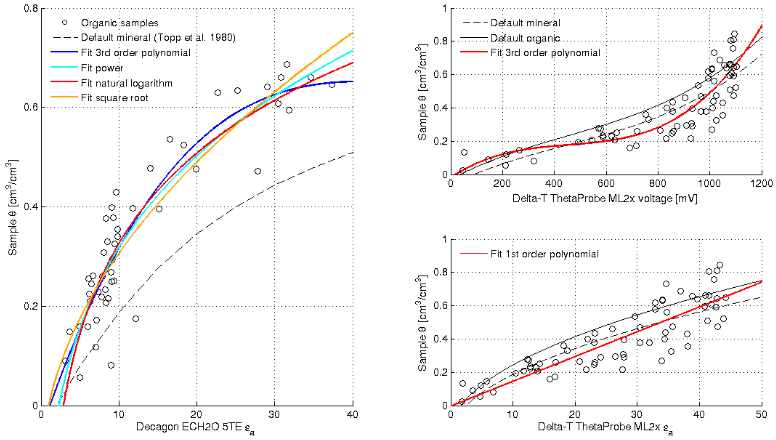

Figure 3. Fitting functions for the Decagon 5TE apparent relative permittivity ε_a (left column), and ThetaProbe voltage [mV] (upper right column) as well as ε_a (lower right column) against volumetric moisture content θ including manufacturer's default calibration curves for the organic soil layers (SOM > 30 %).

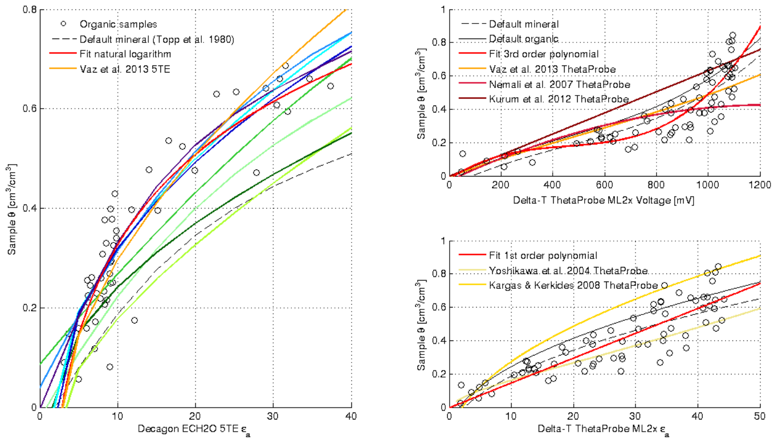

Figure 4. Comparison between reported pedrophysical and empirical relationships applied to our data measured in organic soil layers for the Decagon 5TE apparent relative permittivity ε_a (left column), and ThetaProbe voltage [mV] (upper right column) as well as ε_a (lower right column) against volumetric moisture content θ including respective manufacturer's default calibration curves and best fits.

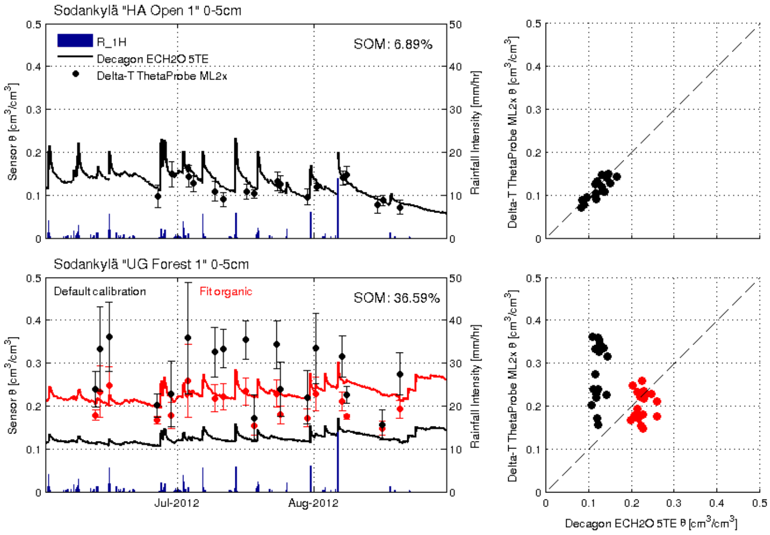

Figure 5. Time series (left column) and scatter plots (right column) for the soil moisture (θ) measured at 0–5 cm depth by ThetaProbe (average of 5 readings with standard deviations as errorbars) and Decagon 5TE sensors at the Sodankylä “HA Open 1” (upper row: low organic mineral soil, SOM = 6.89 %) and “UG Forest 1” (lower row: organic substrate, SOM = 36.59 %) network stations during summer 2012. Hourly rainfall intensities (R_1H) from Tähtelä are plotted along. Details on the applied calibration functions (default in black and newly derived in red) as well as corresponding statistics are given in Table 7.