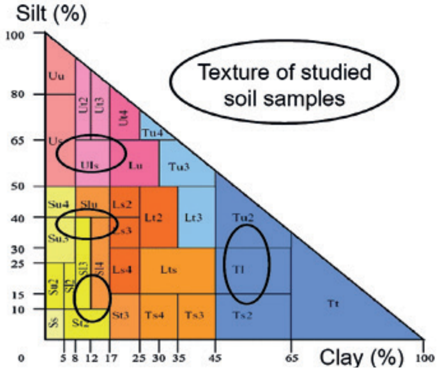

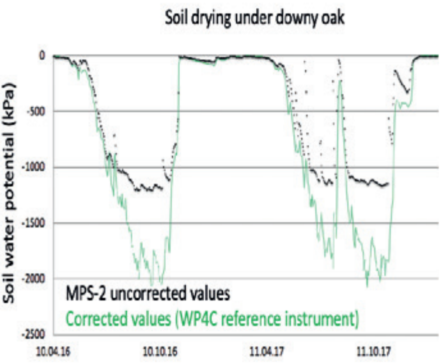

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CH-8903 Birmensdorf

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Authors

Lorenz Walthert (corresponding author)
Swiss Federal Institute for Forest, Snow and Landscape Research WSL,
Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland, lorenz.walthert@wsl.ch

Douglas R. Cobos, METER Group, Inc., 2365 NE Hopkins Ct., Pullman, WA 99163, USA
Washington State University, Dep. of Crop and Soil Sciences, Pullman, WA 99163, USA

Patrick Schleppi, Swiss Federal Institute for Forest, Snow and Landscape Research WSL,
Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

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Abstract

Soil matric potential quantifies water availability in soils. Low soil matric potentials are difficult to measure with most *in situ* techniques. This is also the case for the widely-used dielectric *MPS-2* sensor. This probe determines matric potential indirectly from the measured water content in its porous sensor ceramics using dielectric permittivity as a proxy for water content. The accuracy of *MPS-2* readings was analyzed in desiccation experiments using 13 soils with different texture and organic carbon content and a *WP4C* dewpoint potentiometer as reference instrument. Further, it was explored whether observed inaccuracies relate to sensor calibration, confounding dielectric effects, or the water release characteristics of the sensor ceramics. Above –1000 kPa, the *MPS-2* readings were accurate in all tested soils with a mean deviation of 3% to the reference values. Below –1000 kPa, *MPS-2* readings were increasingly higher than the reference in all tested soils, but the deviation from the reference depended on soil type. Poor factory calibration of the sensors, soil texture dependent differences of water flow at the soil-ceramic interface, and dielectric effects are supposed to be the main reasons for the low and soil-type-specific *MPS-2* sensor accuracy in dry soils. Nevertheless, the high consistency of the *MPS-2* readings allowed us to derive soil-type-specific equations to improve the accuracy of measurements to values as low as –4000 kPa. We recommend applying the equations to any *MPS-2* readings below ~ –1000 kPa to obtain more reliable data and thus an improved insight into the role of soil water in ecosystems.

Keywords

dewpoint potentiometer, dielectric sensor, drought, electromagnetic sensor, osmotic potential, soil water potential

1 Introduction

Water potential is a measure of the energy state of water. It quantifies water availability in systems such as plants or soils and is a direct control of many biophysical processes (Novick et al., 2022). Water potential further co-determines the size of the hydraulic potential, the driving force for water movement. Total water potential (Ψ_t) is the sum of four components, namely gravitational (Ψ_g), matric (Ψ_m), osmotic (Ψ_o), and pressure (Ψ_p) potential (Nobel, 1999). Soils bind water through matric forces, Ψ_o can be important in saline soils, Ψ_g is meaningful only in wet soils, and Ψ_p results from external pressure on soil water. In our study that uses soil samples, only Ψ_m and Ψ_o are relevant, and soil water potential (Ψ_w) is then the sum of Ψ_m and Ψ_o.

The present study aimed to examine the performance of the widely-used dielectric *MPS-2* sensor (METER Group, USA and Germany) in measuring matric potential. Under the assumption of hydraulic equilibrium, Ψ_m in the soil is equal to Ψ_m measured in the porous ceramic discs of the sensor that are embedded in the soil. The sensor first determines bulk dielectric permittivity in its ceramic discs and relates it to volumetric water content using sensor specific calibration functions. Then, the water content is translated into a potential based on the moisture characteristic curve of the ceramic discs (details see section 2.3.1).

Bulk dielectric permittivity is a complex composite, consisting of a real and an imaginary part. The real part of dielectric permittivity is a measure of a material's ability to hold charge and propagate electromagnetic waves when an electric field is applied while the imaginary part is a measure of energy absorption, named dielectric loss, within the material (Mohamed & Paleologos, 2018). For a given measurement frequency, the magnitude of the real part of dielectric permittivity in porous media is determined primarily by their moisture content (Hardie, 2020), because the permittivity of water (~ 81 at 20°C) is much larger than that of mineral components (3–5) and air (~ 1). The imaginary part of dielectric permittivity is influenced by several factors such as temperature, aqueous phase electrical conductivity and measurement frequency (e.g. Chen & Or, 2006; Seyfried & Grant, 2007; Topp et al., 1980; Wraith & Or, 1999). Dielectric sensor development focused on improving measurements of the real part of bulk dielectric permittivity by using frequencies near or above 100 MHz, but did not eliminate the error associated with the contribution of the imaginary part to bulk dielectric permittivity (Hardie, 2020). Predicted moisture contents from measurements of bulk dielectric permittivity can thus be distorted by factors influencing the imaginary part of permittivity if these factors are not considered adequately for sensor calibration.

Matric potential readings from the dielectric *MPS-2* sensors in dry soils are strongly affected by temperature, as demonstrated by Walthert and Schleppi (2018). These authors provided equations that remove spurious temperature effects from *MPS-2* readings and thus improve data quality. However, it is still unclear how accurately *MPS-2* sensors measure Ψ_m in dry soils. While some tests accredited the *MPS-2* sensors a satisfactory accuracy down to –1000 kPa (Degré et al., 2017; Walthert & Schleppi, 2018), it is still unknown how *MPS-2* sensors perform in soils drier than –1000 kPa, even though their measurement range is declared to go down to –100,000 kPa (Decagon, 2015). Comparisons with a heat capacity sensor (*ecoTech pF-Meter*) in forest soils indicated that temperature corrected *MPS-2* matric potential readings are too high in dry soils with an often occurring but implausible levelling of Ψ_m at around –1000 kPa during midsummer periods (Walthert & Schleppi, 2018). Accurate soil water potential data below –1000 kPa, however, are a precondition for studying the functionality and environmental conditions of many living organisms in terrestrial ecosystems. Plants such as shrubs and trees are able to generate leaf water potentials considerably lower than –1000 kPa by transpiration-induced water loss (Aussenac & Granier, 1978; Ducrey, 1998; Schuldt et al., 2020; Walthert et al., 2021). As a consequence, Ψ_w in soils reaches well below the so-called permanent wilting point of –1500 kPa, which represents Ψ_w at which sunflowers start to wilt (Richards & Weaver, 1943). In temperate forests, for example, Ψ_w as low as –2000 to –3000 kPa have been measured with high-end sensors in several studies (e.g., Bréda et al., 1995; Walthert et al., 2021; Warren et al., 2005). While low plant water potentials have been measured accurately *in situ* for decades using the pressure chamber (Scholander et al., 1965), low soil water potentials are still difficult to quantify with most *in situ* techniques. This study aimed to evaluate the accuracy of the *MPS-2* sensor in a variety of soils by use of a psychrometric potentiometer as a reference instrument. In addition, it sought to find ways to improve the accuracy of *MPS-2* readings in dry soils. More specifically, it was our aim to test whether deviations between the *MPS-2* sensor and the reference instrument are soil-type specific and may relate to error associated with the contribution of the imaginary part to bulk dielectric permittivity, and/or may depend on a soil-type-specific drainage of the porous ceramic discs. Lastly, as *MPS-2* sensors measure Ψ_m but potentiometers the sum of Ψ_m and Ψ_o, it is fundamental to assess whether Ψ_o contributes to the deviation between readings from the *MPS-2* sensors and the reference instrument. To sum up, as the most important added value, our study sought to provide equations for improving the accuracy of *MPS-2* readings in dry soils, since such data are a prerequisite to understand water relations in the soil–plant–atmosphere continuum under drought.

2 Materials and Methods

2.1 Soil samples

As the accuracy of *MPS-2* readings may depend on soil properties, our study included 13 soil samples covering a wide range of texture and organic carbon (OC) content (Table 1). The samples were divided into six groups on the basis of texture and OC content. Four groups consisted of soils with a predominant fraction of either sand (S), silt (U), or clay (C), or with high fractions of both silt and sand (U-S). With an average OC content of 0.9%, these four soil groups were poor in humus. Another soil group (U-S-H) contained silty and sandy topsoils with 3.9% OC on average. Finally, an organic layer with 30.5% OC was included. All soil samples were collected from non saline Swiss forest soils.

Table 1: Characteristics of the 13 soil samples. The samples are divided into six soil groups according to their texture and organic carbon content (OC). EC: electrical conductivity (1:1 soil to water ratio); underscore: main characteristic of the soil groups.

Soil sample	Location	Geology	Depth	Soil group[a]	Sand	Silt	Clay	OC	pH	EC
			cm		%	%	%	%		µS/cm
B	Chippis	Rockslide	70–90	S	68	21	11	1.5	7.4	540
G	Reiden	Tertiary sandstone	40–110	S	73	16	11	0.8	6.9	370
A	Saillon	Loess	70–90	U	35	60	5	0.4	7.7	235
I	Mels	Moraine	40–60	U	21	63	16	1.1	3.8	220
F	Ottoberg	Tertiary marl	90–100	C	10	34	56	0.2	7.4	325
J	Bärschwil	Mesozoic limestone	70–100	C	27	16	57	0.8	7.4	256
M	Hohtenn	Moraine	70–80	U-S	54	37	9	1.7	7.4	296
N	Vétroz	Moraine	70–80	U-S	55	35	10	1.0	7.5	278
C	Chippis	Rockslide	5–20	U-S-H	27	60	14	2.5	5.2	530
D	Vétroz	Moraine	5–20	U-S-H	23	57	20	2.4	7.3	515
H	Chippis	Rockslide	2–5	U-S-H	37	48	15	6.6	7.3	494
L	Hohtenn	Moraine	15–25	U-S-H	54	33	13	4.0	7.1	644
K	Bannwald	Flysch	Organic layer	H	na	na	na	30.5	2.9	1054

[a] Soil group: S sand, U silt, C clay, U-S silt-sand, U-S-H silt-sand-humus, H humus

2.2 Soil analyses

Soil pH was measured potentiometrically in a suspension of 2-mm sieved soil samples in 0.01 M $CaCl_2$. The organic carbon content was analyzed by combustion of milled soil samples with a CN analyzer NC 2500 (CE Instruments, Italy) whereby any existing carbonates were removed by HCl vapor prior to combustion (Walthert et al., 2010). Electrical conductivity (EC) of the soil samples was assessed by shaking 30 mL of dried and 2-mm sieved soil with the same volume of distilled water, waiting 4 h, filtering the obtained slurry, and measuring EC in the filtrate at 20°C. Particle size (texture) was analyzed with 2-mm sieved soil by sedimentation according to Gee and Bauder (1986).

2.3 Sensors

2.3.1 *MPS-2* matric potential sensor

The dielectric matric potential sensor *MPS-2* (Decagon Devices, Inc., Pullman, WA, USA) measures bulk dielectric permittivity indirectly by capacitive readings at a frequency of 70 MHz, i.e., by quantifying the charge held in the porous ceramic discs in the sensor. The dielectric permittivity is determined by using a factory calibration relating capacitance to permittivity. Permittivity is then converted into water content, which is finally transformed into Ψ_m based on the sensor's log-log moisture characteristic curve that is assumed to be linear between the two calibration points, water saturated at 0 kPa and air-dry at –100,000 kPa (Decagon, 2015). *MPS-2* sensors record temperature in addition to Ψ_m. Only *MPS-2* sensors with the factory calibration were used in our study.

MPS-2 accuracy is ±(25% of reading + 2 kPa) from –9 to –100 kPa (Decagon, 2015). Below –100 kPa, the accuracy is not quantified by the manufacturer and, moreover, strongly depends on the soil temperature (Walthert & Schleppi, 2018). However, some information has been published about the accuracy of *MPS-2* readings below –100 kPa, valid at 22°C. From –100 to –500 kPa, accuracy is considered good (Supplemental Fig. S1; Degré et al., 2017), from –500 to –1000 kPa it is moderate, and below around –1000 kPa the sensors still respond to changes of Ψ_m but may not give accurate measurements (Supplemental Fig. S1; Walthert & Schleppi, 2018).

2.3.2 *WP4C* reference sensor

Vapor pressure methods are ideal for measuring Ψ_w in dry soil samples (Gee et al., 1992; Novick et al., 2022). The dewpoint potentiometer *WP4C* (METER Group, Inc., Pullman, WA, USA) uses the chilled-mirror dewpoint technique. When dew appears on a mirror when it is cooled down, its reflectance changes and both the dewpoint temperature and the sample temperature are measured. From this, Ψ_w of the soil sample can be calculated using the Kelvin equation (Gee et al., 1992). The measurements are carried out in a sealed sample chamber once equilibrium between the vapor pressure of the air and the sample is achieved. The *WP4C* measures Ψ_w as the sum of Ψ_m and Ψ_o of the sample. A detailed description of the *WP4C* reference instrument can be found in METER (2020).

The accuracy of the *WP4C* is ±0.05 MPa for measurements above –5 MPa and 1% from –5 to –300 MPa (METER, 2020). The accuracy is limited in the wet end of the water potential range. At –200 kPa, e.g., the accuracy is ±25% and at –100 kPa ±50%. Therefore, in our study, the *WP4C* was considered to be suitable as a reference instrument for Ψ_w lower than about –500 kPa.

2.4 Consistency between *MPS-2* and *WP4C* readings in soil samples: experimental setup

The consistency between *MPS-2* and *WP4C* readings in soil samples was tested with five sensors representing the median 5 out of a pool of 15 *MPS-2* sensors produced in 2016. For these tests, the 13 soil samples described above (section 2.1 and Table 1) were used for which a volume of 4000–5000 cm^3 was available in each case. The tests were performed at seven target matric potentials around –250, –500, –750, –1000, –1500, –2000, –2500 kPa, resulting in a total of 91 tests (13 soils, each at 7 target Ψ_m). The target Ψ_m were adjusted according to Walthert and Schleppi (2018), which allows to produce soil samples with a reasonably uniform moisture distribution (with a water content of sub-samples having a coefficient of variation CV < 1%). In short, the target Ψ_m were adjusted by adding water to the samples or removing water from them. Water was removed by heating the samples at around 40–45°C. Once the *MPS-2* sensors indicated that a target Ψ_m was roughly achieved, the soil sample was intensively mixed by hand, transferred to a plastic container and the five *MPS-2* sensors were buried fully and vertically in the soil. The container was then wrapped in plastic foil in order to minimize evaporative water loss. After that, the container was placed in a climate chamber where temperature was kept at approximately 22°C. Soil temperature and Ψ_m were recorded every 5 minutes by the *MPS-2* sensors and stored in a *Decagon Em50* data logger. The measurements for the subsequent data evaluation were taken when Ψ_m readings remained constant and thus indicated no flow conditions. Soil temperature was always 22°C (±0.1°C) because this corresponds to the temperature of the factory calibration of the *MPS-2* sensors. Moreover, 22°C is the temperature to which *MPS-2* readings are corrected in Walthert and Schleppi (2018). Each of the 91 tests took about 3–5 days until Ψ_m readings in the *MPS-2* sensor ceramic discs remained constant. In most of these tests, the direction of water flow was from the moister ceramic disc into the drier surrounding soil.

At the end of each test, a soil sample of around 100 cm^3 was taken from around the buried *MPS-2* sensors in order to measure the reference water potential and the water content for the water retention curves of the soil. From this sample, Ψ_w was measured in four replications with the *WP4C* potentiometer at 22°C. Finally, for gravimetric water content determination, the remaining soil from the sample was weighed and then dried at 105°C until the weight remained constant. The water content was calculated by subtracting the oven-dry weight from the fresh weight and dividing by the dry weight. Soil density was not assessed because of its minor importance for Ψ_m measurements (Campbell & Gardner, 1971).

With the same experimental setup as described above, it was tested whether *MPS-2* sensors manufactured in different years behave consistently. For this purpose, five *MPS-2* sensors from 2012 and another five from 2014 were used, in addition to the five sensors from 2016. Contrary to the sensors from 2016 (median 5 out of a pool of 15 *MPS-2* sensors), the sensors from 2012 and 2014 were selected randomly from our stock of older *MPS-2* sensors. Consistency across *MPS-2* sensors manufactured in different years was tested using only one soil sample (sample D) because sensor consistency across manufacturing years was not expected to depend on soil type.

2.5 Comparing *MPS-2* and *WP4C* readings both from ceramic discs

By comparing the water retention curves of the ceramic discs derived from *MPS-2* readings on the one hand and from *WP4C* reference measurements on the other hand, it was intended to check the accuracy of the *MPS-2* sensor calibration. To this purpose, 10 *MPS-2* sensors were embedded in soil sample B, a soil with an intermediate water retention characteristic (Fig. 1) and electrical conductivity (Table 1). The water retention of the ceramic discs was recorded at four moisture levels around –500, –1000, –2000 and –3000 kPa. Five *MPS-2* sensors delivered Ψ_m of their own ceramics while the ceramics from another five *MPS-2* sensors were measured with the *WP4C* in order to get Ψ_w. For *WP4C* measurements of the ceramics, one ceramic disc per *MPS-2* sensor was dismounted, cleaned with a brush, weighed and inserted into the *WP4C* within 30 sec after sensor removal from the soil sample. The water content of the ceramics was determined as described in section 2.4. To get Ψ_m from the *WP4C* measurements, Ψ_o was subtracted from Ψ_w (Ψ_o was assessed as described in section 2.6).

2.6 Osmotic potential

The contribution of Ψ_o to *WP4C* readings of Ψ_w was tested by use of *MPS-2* ceramic discs. Ceramic discs were preferred to soil samples not only because of their higher chemical inertness, i.e., low capacity for ad- and desorption of ions, but also owing to their stable physical structure while simulating a porous soil sample. Conceptually, Ψ_w of drying ceramic discs should be measured at different moisture levels whilst the individual ceramic discs hold solutions differing in EC. Ceramic discs holding deionized water should provide Ψ_m, as Ψ_o is expected to be negligible when EC is very low. For a given moisture level, Ψ_o of a sample corresponds to the difference between Ψ_w of this sample and Ψ_m of the sample holding deionized water. Our experiment included extracts of four soil samples differing in EC and soil texture (Table 1), namely samples A (silt), B (sand), F (clay) and K (humus). The extracts represented the filtered soil solutions collected during the assessment of EC (see section 2.2). For comparison, a saline NaCl-solution with an EC of 6000 µS/cm was included. All tests were made with one ceramic disc per sample except for the Ψ_m reference values that were assessed with three ceramics holding deionized water. The ceramic discs needed for this experiment were dismounted from *MPS-2* sensors. During sample preparation, all ceramic discs were first flushed and then submerged in deionized water for five days. After that, they were dried for 24 hours at 105°C and then submerged in the solutions for ten days at 3°C. Finally, the initially saturated ceramic discs slowly desiccated under ambient conditions at an air temperature of about 20°C and, from time to time, Ψ_w of the ceramics and Ψ_m of the ceramics holding deionized water were measured with the *WP4C* at 22°C. The corresponding water contents of the ceramic discs were determined as described in section 2.4.

2.7 Statistical analyses

Preliminary analyses to develop the correction equations based on the measured matric potentials (*MPS-2*) and water potentials (*WP4C*) resulted in highly inhomogeneous residuals. All potentials Ψ were thus log-transformed to pF values before further statistical analyses (Eq. 1).

$$pF = \log(-\Psi[\mathrm{hPa}]). \qquad (1)$$

For each soil and moisture level, data from five *MPS-2* sensors on the one hand and from four *WP4C* measurements on the other hand were averaged and considered as one data pair for regression analyses. Data were then divided into soil groups according to their texture and OC content (Table 1). As our goal was to obtain a correction of the *MPS-2* readings towards the *WP4C* reference, the former was used as the independent and the latter as the dependent variable. Polynomial regressions were tested and evaluated according to their coefficient of determination (R^2) and to the distribution of their residuals.

3 Results

3.1 Water retention characteristics of the soils and the *MPS-2* ceramic discs

The six soil groups differed in their water retention characteristics as assessed with the *WP4C* dewpoint potentiometer (Fig. 1). As expected, the highest water storage was found for humus, which was followed by clay, and the lowest was found for silt, sand and silt-sand. Compared to the soils, the *MPS-2* ceramic discs had a high percentage of very large pores that drained easily (Fig. 1). At around –3000 kPa, the ceramic discs were nearly completely drained, holding only some 10 mg of water corresponding to a gravimetric water content of about 0.6%. Thus, at around –3000 kPa, the ceramics held at least ten times less water than most soil samples. However, the ceramic discs did not fully dry out in our tests and still hold a small amount of water even at –10000 kPa (Fig. 1).

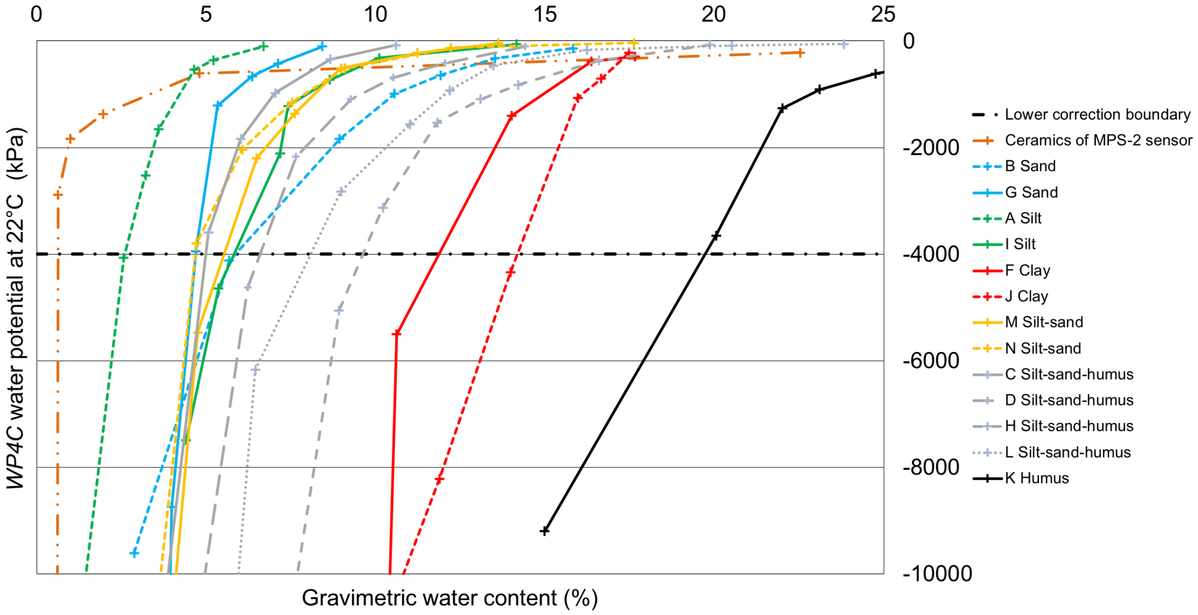

Figure 1: Water retention curves of the studied soil samples and the *MPS-2* ceramic discs. The 13 soil samples are divided into six groups (displayed in different colors) according to their texture and organic carbon content (Table 1). The correction of *MPS-2* measurements with the provided equations should be done only down to –4000 kPa (horizontal dot-dashed line). Note that the water content of sample K (organic layer) was divided by a factor of 2 for better illustration. All water potentials were measured with a dewpoint potentiometer (*WP4C*) and are shown as the mean of four replications (soil samples) or three replications (ceramic discs) measured at 22°C.

3.2 Deviation between *MPS-2* and *WP4C* measurements in soils

Within a range of *MPS-2* readings from –500 to –1000 kPa, the mean deviation between the *MPS-2* and *WP4C* measurements over all 13 soil samples was 3% (min. –30%, max. +30%), indicating a good agreement between the two sensor measurements in all soils (Fig. 2). Below *MPS-2* values of –1000 kPa, the *MPS-2* sensors reported distinctly moister conditions for all 13 soil samples compared with the *WP4C* reference (Fig. 2). In detail, between –1000 and –4000 kPa, the *MPS-2* sensors still clearly responded to changes in soil water potential in all soil samples, but below –4000 kPa their responsiveness strongly decreased in most soil samples (Fig. 2) and the *MPS-2* matric potentials were always at least 50% higher than the *WP4C* reference values. Besides this general pattern, the *MPS-2* sensors showed a soil-type-specific behavior. The worst agreement between the *MPS-2* and *WP4C* measurements was found in clay, sand and silt-sand-humus, where the *MPS-2* matric potentials were much higher than the *WP4C* reference values (Fig. 2). In humus, silt and silt-sand the *MPS-2* and *WP4C* measurements agreed better. While the *MPS-2* sensors were generally inaccurate in dry soils < –1000 kPa, there was high consistency across the five *MPS-2* sensors over all moisture levels and all soil samples. The variation coefficient (CV) of the five *MPS-2* sensors was always smaller than 24% (mean 12%) in all 91 tests.

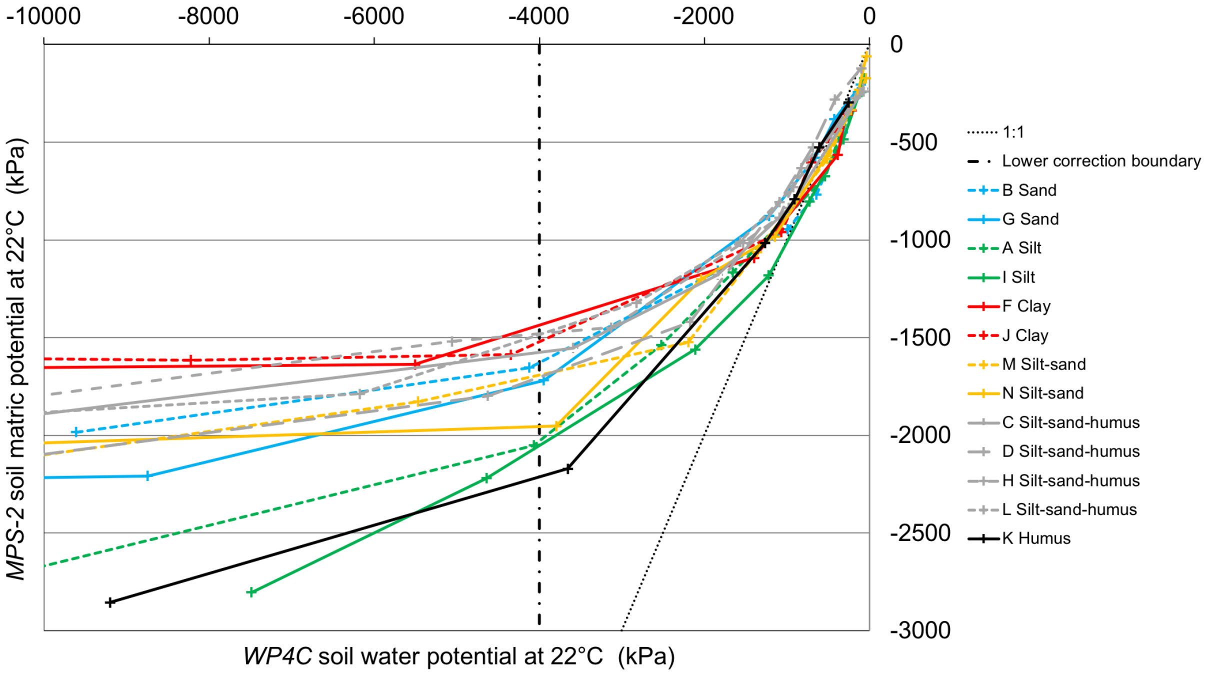

Figure 2: Deviation between the soil matric potential from *MPS-2* sensors and the soil water potential from the reference instrument, a dewpoint potentiometer (*WP4C*). The 13 studied soil samples are divided into six groups (displayed in different colors) according to their texture and organic carbon content (Table 1). The vertical dot-dashed line represents the -4000 kPa application limit of the equations proposed in this contribution. The measurement points represent the mean of five replications for *MPS-2* and four replications for *WP4C*, each measured at 22°C. For the correction range between about –500 and –4000 kPa (*WP4C* values), the variation coefficient (CV) of the five *MPS-2* measurements for each soil sample and water potential level was 12% on average, and the corresponding value for *WP4C* measurements was 4%.

3.3 Equations for improving *MPS-2* data accuracy in dry soils

In all soils, the *MPS-2* and *WP4C* measurements were similar down to a water potential of approximately –1000 kPa. Below –1000 kPa, the *MPS-2* measurements remained consistent with each other but did not follow the water potential decrease of the *WP4C*. Considering the inherent superiority of dewpoint potentiometers in dry soils (Gee et al., 1992; Novick et al., 2022), the *WP4C* values were considered as a reference and the *MPS-2* values were corrected in a way that they approached this reference as precisely as possible. Because the standard deviation of the measured Ψ_m and Ψ_w clearly increased with the mean absolute values, the prerequisite of homogeneous variance for a regression analysis was not satisfied. Logarithmic transformation of the potentials to pF values (Eq. 1) solved this problem.

The difference between the readings of the two sensor types appeared to be related to the texture and OC content of the soils. For each soil group, a second-degree polynomial (Eq. 2) was fitted:

$$pF_c = a + b \cdot pF_m + c \cdot pF_m^2 \qquad (2)$$

where pF_m is the measured pF and pF_c the corrected one.

All the obtained regressions had a coefficient of determination of at least $R^2 = 0.93$ (Table 2). Depending on the soil group, the regression line crossed the 1:1 line between pF 3.75 and pF 3.96, corresponding to Ψ of –570 and –910 kPa (Fig. 3, Table 2; for regression lines with 95% confidence interval see Supplemental Fig. S2). Between these points and the predicted pF value of 4.6 (approx. –4000 kPa), the regression curve for sandy soils did not differ significantly from those of the silt-sand, silt-sand-humus and clay soil groups. In all other pairwise comparisons, the curves lied partly outside the 95% confidence interval of each other and could thus be considered as significantly different (Supplemental Fig. S2).

Table 2: Results of the regressions per soil group, with coefficients of degrees (a) 0, (b) 1, and (c) 2 (see Eq. 2). RMSE: root mean square error. pF_{min}: intersection of the regression curve with the 1:1 line, i.e. the minimum value needed to apply the equation. Ψ_{max}: the same value as pF_{min} but expressed as a water potential.

	Sand	Silt	Clay	Silt-sand	Silt-sand-humus	Humus
a	17.219±7.541	1.328±2.148	63.963±19.612	14.508±6.818	15.002±4.081	5.610±4.811
b	-8.980±3.917	-0.492±1.115	-33.381±10.026	-7.413±3.516	-7.825±2.145	-2.274±2.434
c	1.428±0.505	0.292±0.144	4.603±1.275	1.203±0.451	1.283±0.280	0.474±0.306
R^2	0.94	0.99	0.93	0.96	0.94	0.99
RMSE (pF)	0.199	0.070	0.250	0.144	0.184	0.077
n	14	14	12	12	29	7
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002
pF_{min}	3.881	3.954	3.961	3.909	3.811	3.755
Ψ_{max} (kPa)	-760	-899	-914	-811	-647	-569

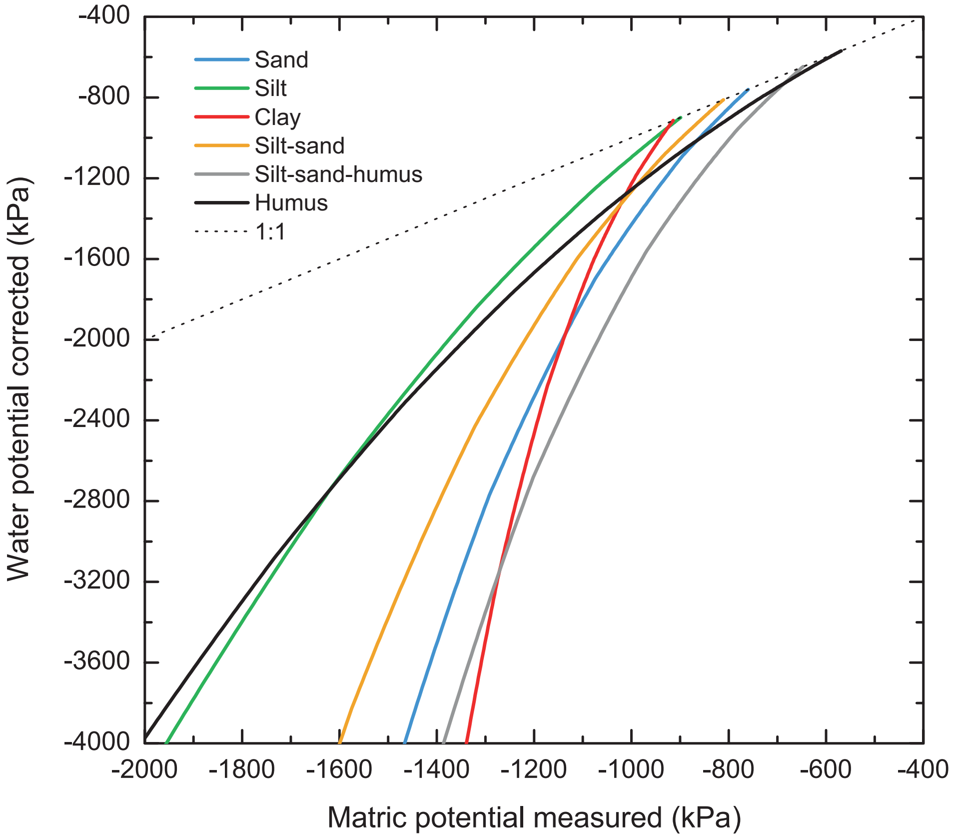

Figure 3: Regression curves (2^{nd} degree polynomials based on the pF scale) for the correction of *MPS-2* measurements. See Table 2 for the parameters of these regressions. Each curve represents a soil group according to Table 1. The reference soil water potentials, i.e. the corrected water potentials, were measured with a dewpoint potentiometer (*WP4C*). All values refer to the reference temperature of 22°C.

3.4 Deviation between *MPS-2* and *WP4C* measurements both with ceramic discs

MPS-2 and *WP4C* readings with ceramic discs were similar under moist conditions but below –1000 kPa, Ψ_m of *MPS-2* was increasingly higher than reference Ψ_w of *WP4C* (Supplemental Fig. S3). This is similar to measurements made with soil samples (Fig. 2). Osmotic potential contributed only marginally to the observed differences between *MPS-2* and *WP4C* readings in the ceramic discs. Furthermore, the *WP4C* readings revealed that the log-log water retention curve of the *MPS-2* ceramic discs is not linear between water saturation and air dry (Supplemental Fig. S3). Linearity, however, is assumed for the original two-point calibration of the *MPS-2* sensors (see section 2.3.1).

3.5 Osmotic potential

The magnitude of Ψ_o depended on the amount of water in the ceramic discs, i.e., the degree of dehydration, and on the original electrical conductivity of the extracts (Supplemental Fig. S4). At a water content of 20% in the ceramic discs, the contribution of Ψ_o to Ψ_w amounted to 5–11% for the extracts of the mineral soil samples A (silt), B (sand), and F (clay). For the humus sample K and the saline sample, Ψ_o contributed 49 and 80%, respectively. At 1% water content, the contribution of Ψ_o increased to 17–32, 80, and 95% for the samples mentioned above. In the application range of our equations, thus for *WP4C* Ψ_w values of –1000 to –4000 kPa (for a justification of this range see section 4), the soil samples retained much more water than the ceramic discs (Fig. 1). Therefore, taking into account the concentration of solutes accompanying the evaporation, the contribution of Ψ_o was expected to be lower in the soil samples than in the ceramic discs. In the mineral soils A, B and F, Ψ_o can be expected to contribute 0.5–6.5% to Ψ_w while in the humus sample K, its contribution is expected to be around 35–40% (Supplemental Fig. S4).

3.6 Consistency of readings from *MPS-2* sensors manufactured in different years

Between around –500 and –4000 kPa (*WP4C* values), the variation coefficient of the 15 tested *MPS-2* sensors manufactured in 2012, 2014 or 2016 was between 15% and 20% (mean 17%) at the four considered moisture levels. No systematic deviations between the sensors were detected during desiccation, with the exception of one *MPS-2* sensor from 2014 that produced outlier data (Supplemental Fig. S5).

4 Discussion

Clear relationships between *MPS-2* and *WP4C* measurements in the tested soils allowed to develop soil-type-specific equations to make *MPS-2* readings more accurate. It will be discussed hereafter why *MPS-2* and *WP4C* readings differed in dry soils, whether the equations are suitable for general use, and how the equations should be applied.

4.1 Reasons for low *MPS-2* sensor accuracy in dry soils

As mentioned above, the *MPS-2* sensor determines Ψ_m from measured capacitance via several conversion and calibration steps. Our tests with *MPS-2* and *WP4C* measurements both from ceramic discs showed an increasing deviation between the measurements of the two devices towards drier conditions (Supplemental Fig. S3), indicating that systematic error, i.e., too moist *MPS-2* readings, originated from an inaccurate calibration of Ψ_m. As *MPS-2* sensors assess Ψ_m but *WP4C* the sum of Ψ_m and Ψ_o, and as Ψ_o can be substantial in drying soils (Abedi-Koupai & Mehdizadeh, 2008; Warren et al., 2005) we checked whether Ψ_o contributed to the observed deviation between *MPS-2* readings and *WP4C* reference values. Osmotic potential measured in the ceramic discs, however, contributed only little to the observed deviation, even when the discs were strongly desiccated (Supplemental Fig. S3). Moreover, as Ψ_o contributed only 0.5–6.5% to Ψ_w in all tested mineral soil samples (Supplemental Fig. S4), Ψ_o cannot explain the generally high deviation between *MPS-2* and *WP4C* measurements in these soils, which again suggests inaccurate factory calibration of the *MPS-2* sensors. With the available data, however, we were not able to attribute the observed sensor inaccuracy to specific steps of the factory calibration.

While we identified poor *MPS-2* sensor calibration as the main reason for the general mismatch between *MPS-2* and *WP4C* readings in dry soils, the observed soil-type-specific *MPS-2* sensor accuracy can be attributed to a soil texture specific extent of ceramic desiccation and soil-type related dielectric effects within the ceramic discs as discussed hereinafter. Our desiccation tests indicated that the *MPS-2* ceramic discs dried out least in clayey and sandy soils and most in silty and organic samples (Fig. 2). We used Ψ_m values measured after 3–5 days, when Ψ_m was constant and suggested cessation of water release from the ceramic discs into the surrounding soil. Under very dry conditions, the total volume of water-filled fine pores in the ceramic discs is very small (Fig. 1). Depending on the texture, this could lead to a pore size discontinuity at the ceramic-soil-interface and an associated texture related cessation of water flow, explaining the observed soil-type-specific differences in the extent of ceramic desiccation at the tested target matric potential levels. Even though we found that, from a *WP4C* perspective, Ψ_o seems to have a minor importance for the deviation between *MPS-2* and *WP4C* measurements in soil samples, Ψ_o could be relevant from the *MPS-2* perspective, because it could influence the imaginary part of the bulk dielectric permittivity, i.e., the loss factor, in the ceramic discs. As mentioned above, the magnitude of dielectric permittivity loss depends on factors such as temperature, salinity, and porosity. While temperature and porosity of the *MPS-2* ceramic discs were constant in all tests, osmotic potential and thus salinity within the ceramic discs increased with desiccation in a soil-type-specific extent (Supplemental Fig. S4). This potentially affected the loss factor and therefore also the measured bulk dielectric permittivity. Consequently, soil-type-specific imaginary dielectric effects may modify the observed general mismatch between *MPS-2* and *WP4C* readings towards drier conditions. Unfortunately, it was not possible to study these processes between –1000 and –4000 kPa in more detail because the ceramic discs contained only a few milligrams of water. With such small amounts of residual water and under ongoing evaporation, experiments with such discs are difficult to reproduce.

Finally, it is noteworthy that the observed too moist *MPS-2* readings could also be generated if the *MPS-2* sensor's electromagnetic field would fringe into the soil and thus include soil water in addition to ceramic water. However, this is unlikely as, for our soil samples, no clear relation was found among the water content of the samples (Fig. 1) and the deviation between Ψ_m from *MPS-2* sensors and Ψ_w from the reference instrument (Fig. 2), neither under moist nor under dry conditions.

To sum up, our study suggests poor sensor calibration as the main reason for the general deviation between *MPS-2* and *WP4C* readings. Nevertheless, the behavior of the *MPS-2* sensor entailed a significantly differing sensor accuracy for each of the tested soil groups. Only the group of sandy soils did not differ significantly from the silt-sand, silt-sand-humus and clay groups. However, because these three differed from each other, the sand group is best kept separate in our interpretations and in potential applications.

4.2 Application of the proposed equations

The comparison of 15 *MPS-2* sensors manufactured in different years showed that the sensors behave quite uniformly in dry soils by taking inaccurate but fairly consistent readings. Therefore, our equations can be used to improve the accuracy of readings from any *MPS-2* sensor. As soil type significantly affected the accuracy of the readings, equations for different soil groups are provided according to their texture and OC content.

No values lower than –4000 kPa should be calculated with the equations (Eq. 2, Table 2) as computed data may become increasingly inaccurate towards even drier conditions. As a first reason, the water storage capacity of the *MPS-2* ceramic is very small below *WP4C* values of around –3000 to –4000 kPa (Fig. 1), meaning that the pore size distribution of the ceramic is inappropriate for measurements at drier conditions where the responsiveness of the *MPS-2* sensors clearly decreased (Fig. 2). Second, the precision of the equations substantially decreased below *WP4C* values of –4000 kPa (Supplemental Fig. S6), indicating a decreasing consistency of the *MPS-2* readings toward drier conditions in all tested soil groups. Third, not going below –4000 kPa means that the uncorrected *MPS-2* readings are above –2000 kPa in all soils (Fig. 3), ensuring compatibility with Walthert and Schleppi (2018). These authors provided equations to remove spurious temperature effects from *MPS-2* matric potential readings. These equations produce minimum values as low as –2000 kPa, valid for a reference soil temperature of 22°C.

The proposed equations amplify the response of the *MPS-2* sensors in their application range down to –4000 kPa. Thus, the improvement of accuracy is obtained at the price of also amplifying the residual, random errors. This is especially the case for exceptionally clay-rich soils, which have the steepest correction curve (Supplemental Fig. S2). Nevertheless, random errors can be estimated by replicate measurements while systematic errors could remain unseen. In this sense, our equations bring a true improvement in the acquisition of data in dry soils.

The application limit of the equations (Eq. 2) at the moist end is soil-type specific. Depending on the soil, the correction is intended to start between –570 and –910 kPa (Table 2), where the curves depart from the 1:1 line (Fig. 3). Thus, the use of the equations starts in a range where the *MPS-2* sensors still measure accurately. This somewhat overcautious start of data correction in the relatively moist range is necessary to prevent jumps in the data.

In the tested mineral soils, Ψ_o was always much lower than the prediction error (RMSE) of the proposed equations (Table 2) and therefore was not subtracted from Ψ_w. Thus, *MPS-2* values produced with our equations (Eq. 2) may include a small, but for most applications negligible Ψ_o component in mineral soil samples. To exclude Ψ_o from organic samples, a proportion of around 35% (Supplemental Fig. S4) may be subtracted from Ψ_w to get Ψ_m, if required.

For a reliable and reasonable application of our proposed equations (Eq. 2, Table 2), the following procedure is recommended:

1. In case of probable soil salinity, check the electrical conductivity by using the same volume of soil and distilled water; it should be lower than about 1000 µS/cm.
2. Remove spurious temperature effects from the *MPS-2* readings using equation 2 in Walthert and Schleppi (2018).
3. Delete values lower than –2000 kPa and outlier data, if present.
4. Calculate the pF value of each reading. If readings from several *MPS-2* sensors installed at the same soil depth should be combined, average the pF values rather than the Ψ readings.
5. Select a soil group from Table 1 that is most similar to your soil based on the criteria texture and organic carbon content.
6. Decide whether your *MPS-2* matric potential readings need correction, i.e. whether they are sufficiently low to reach the soil-type-specific application limit of the equations (Table 2).
7. Correct the *MPS-2* readings using the appropriate soil-type-specific equation (Eq. 2, Table 2); do not correct readings that are above the application limit, i.e., where moisture is higher than the application limit.
8. Delete or flag values lower than –4000 kPa.

5 Conclusions

Our soil desiccation experiments with a psychrometric potentiometer as a reference instrument indicated that the generally low *MPS-2* sensor accuracy in dry soils was caused by poor factory calibration. Differences between soil groups, on the other hand, most probably resulted from a soil-type-specific extent of ceramic desiccation modified by imaginary dielectric effects on measured bulk dielectric permittivity. The satisfactory measuring consistency of *MPS-2* sensors produced in different years suggested to apply the proposed soil-type-specific equations to readings from any *MPS-2* sensor. The minimum Ψ values produced by applying the equations are expected to be similar to those measured with high-end sensors in temperate forests under drought, suggesting a reasonable degree of correction. Such improved data from dry soils are required for many applications, such as assessments of drought-induced stress in the soil–plant–atmosphere continuum. For reliable results from the proposed equations, the recommendations presented in section 4.2 should be followed.

Supplemental Material
The supplemental material consists of six figures.

Acknowledgments
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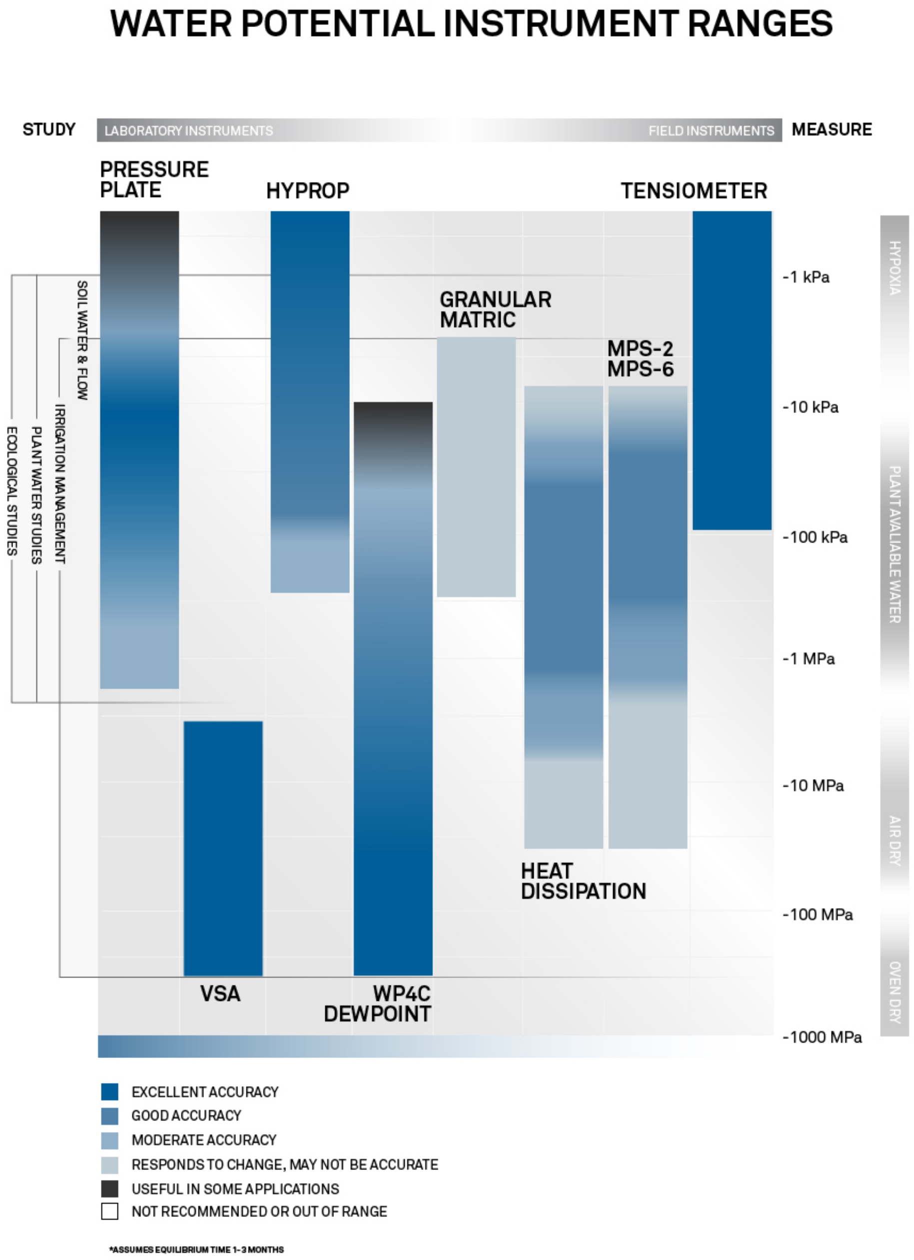
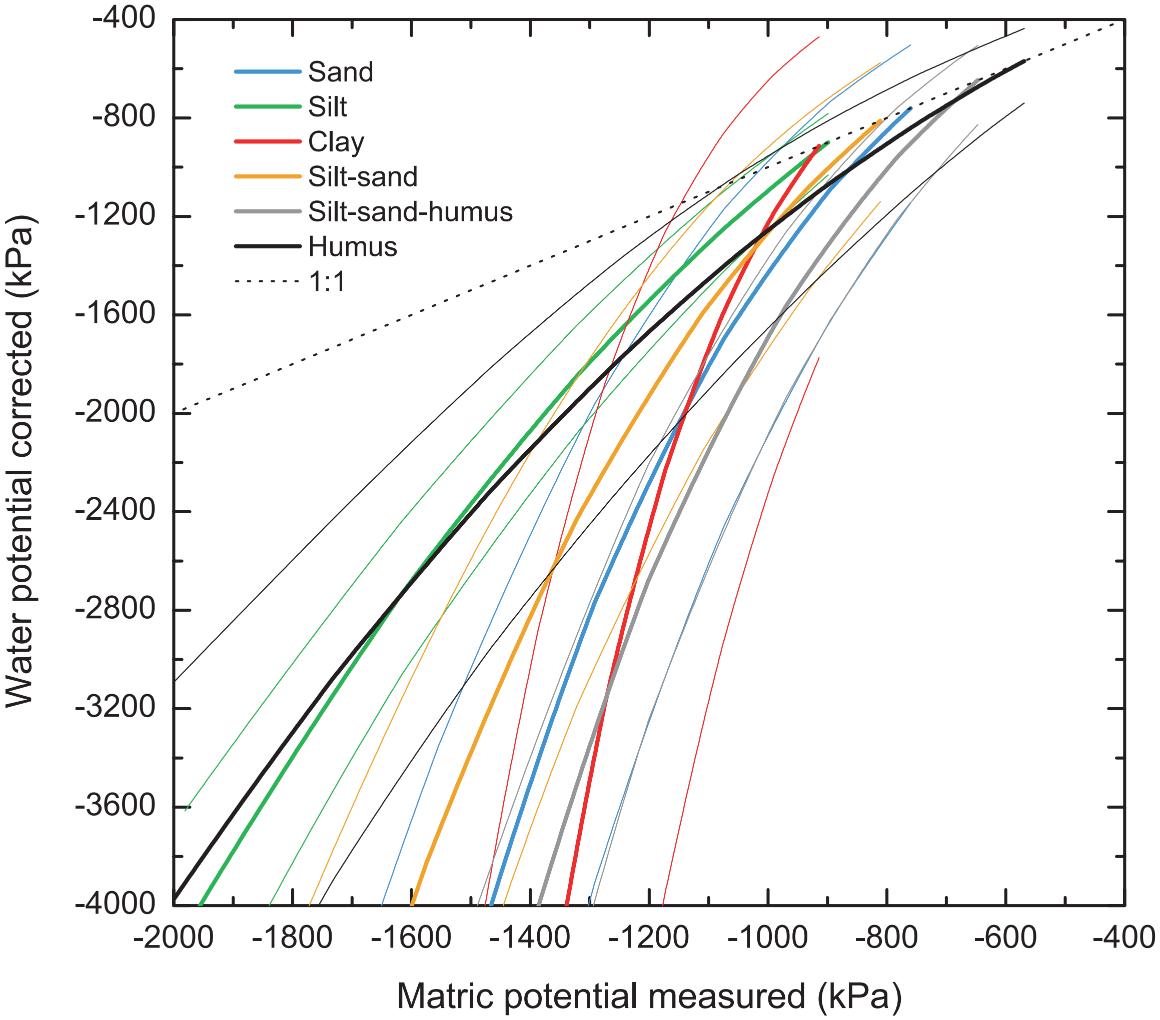
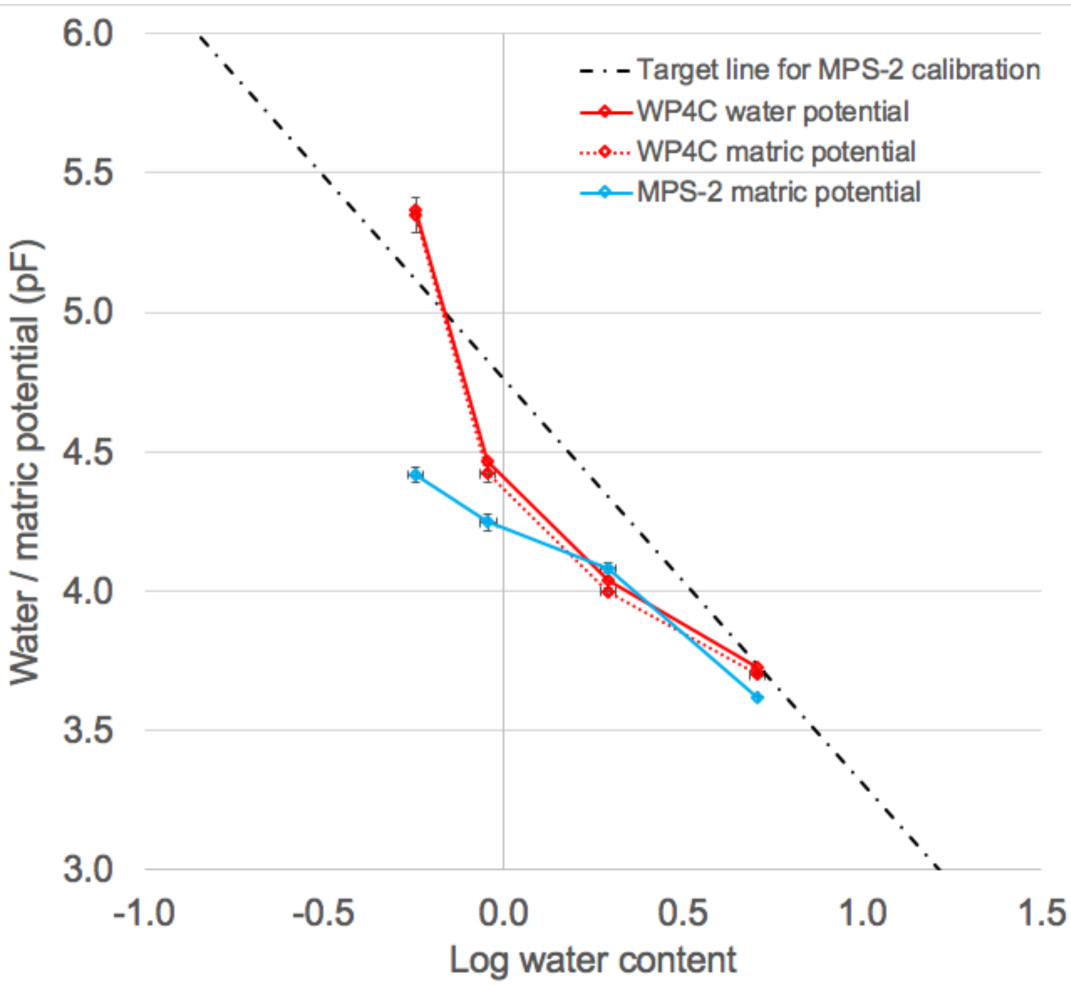
Supplemental Figures



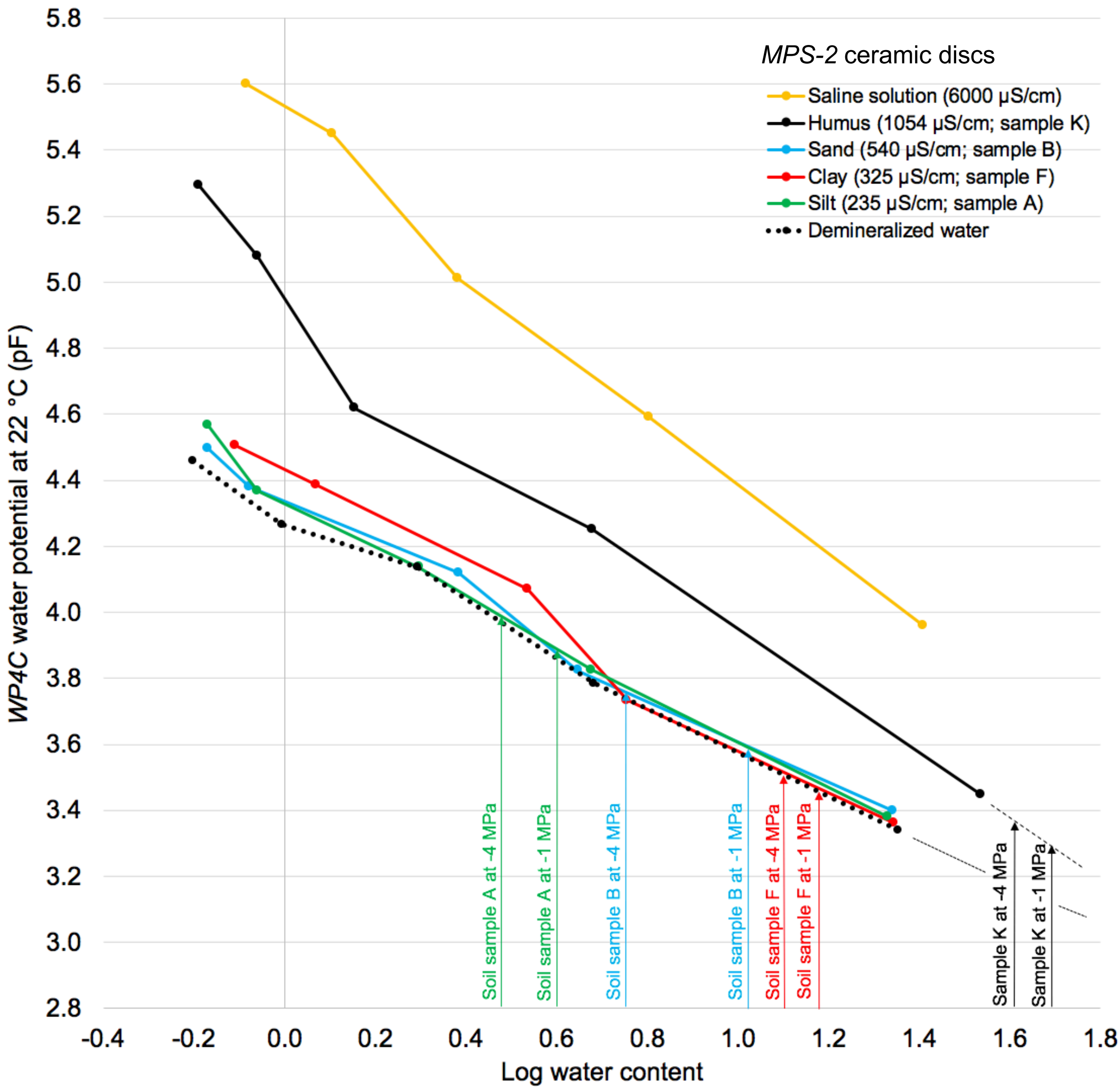
Supplemental Figure S1: Water potential instrument ranges (image source: METER Group, Inc., Pullman, WA, USA).



Supplemental Figure S2: Regression curves (2nd degree polynomials based on the pF scale; bold lines) for the correction of *MPS-2* measurements with the corresponding 95% confidence intervals (thin lines). See Table 2 for the parameters of these regressions. Each color represents a soil group according to Table 1. The reference soil water potentials, i.e. the corrected water potentials, were measured with a dewpoint potentiometer (*WP4C*). All values refer to the reference temperature of 22°C.



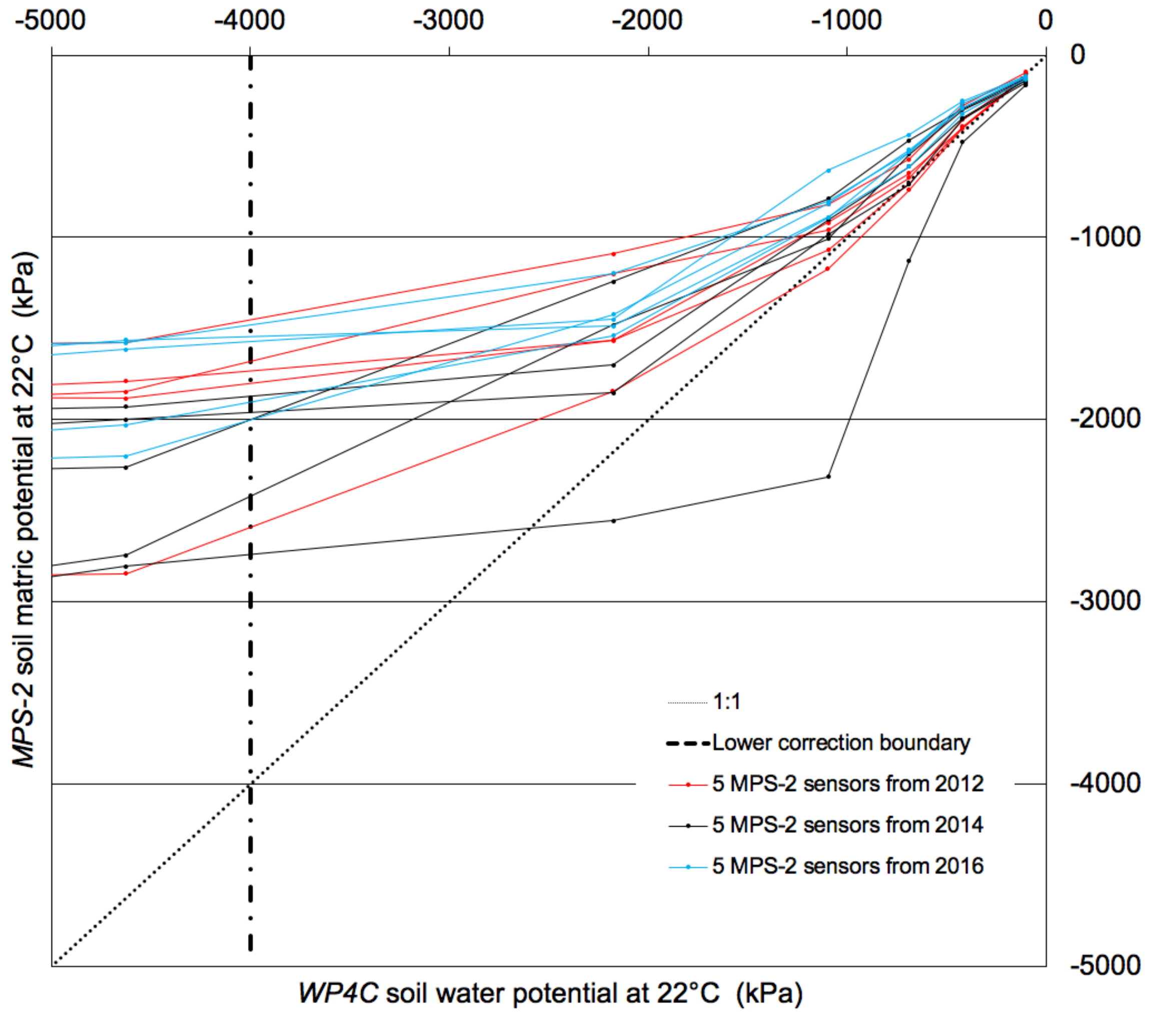
Supplemental Figure S3: Calibration deficiency of *MPS-2* sensors. Deviation between the matric potential from *MPS-2* sensors and the water and matric potential from the reference instrument, a dewpoint potentiometer (*WP4C*) measured in *MPS-2* ceramic discs embedded in soil sample B (sand). Each measurement point represents the mean (±1SE) of five replications measured at 22°C. *WP4C* matric potentials were calculated by subtracting osmotic potential (Supplemental Fig. S4) from water potential. The target line for *MPS-2* sensor calibration connects the two calibration points of *MPS-2* sensors at air dry and water saturation. Air dry (pF 6) corresponds to 0.14% water content, assessed with four at first oven dried ceramic discs after a subsequent storage time of 48 h at 22°C and 50% air humidity. The wet end of the calibration line corresponds to 80% water content at -9 kPa, thus the upper limit of the measuring range of the *MPS-2* sensors (see *MPS-2* operator's manual, 2015).



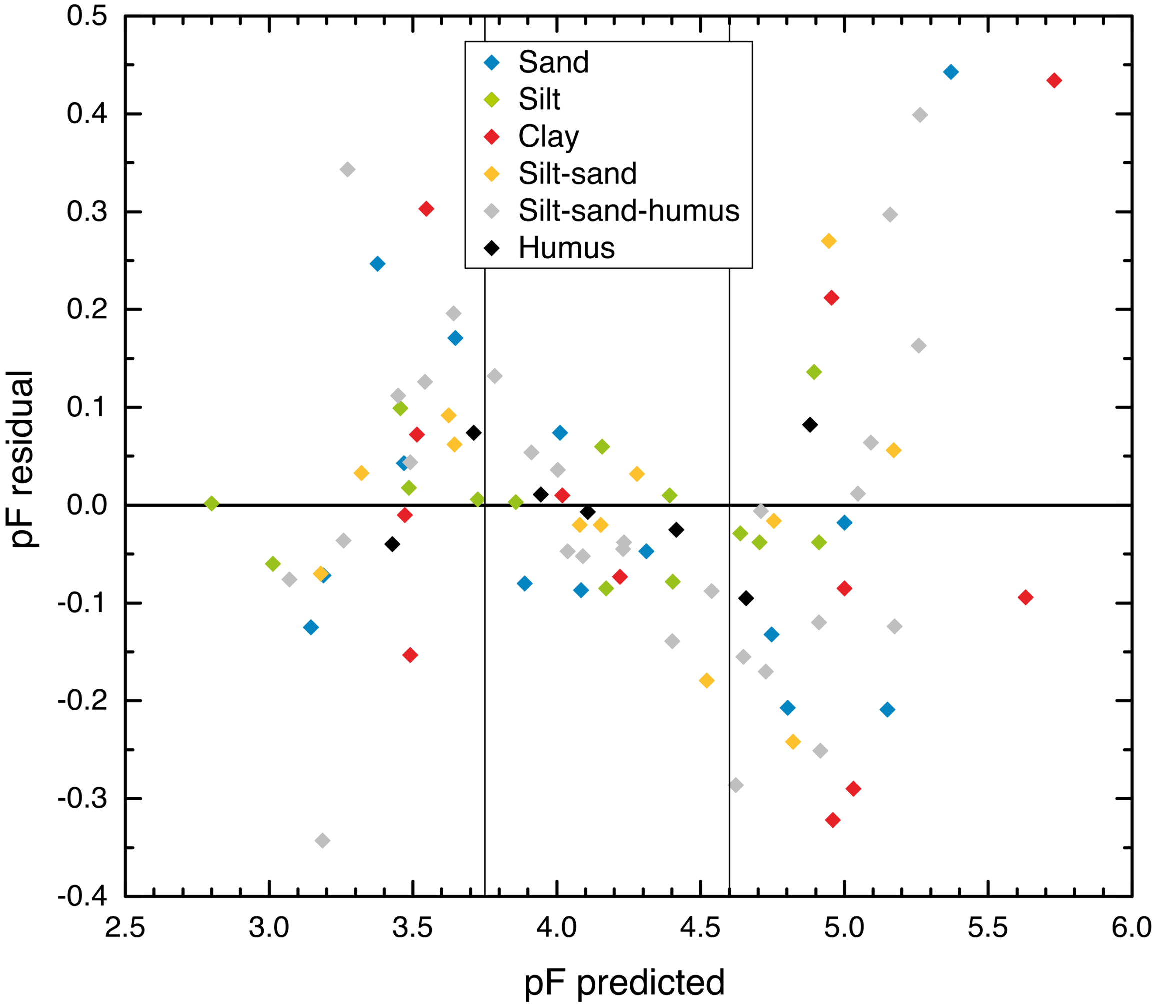
Supplemental Figure S4: Osmotic potential in relation to water content and electrical conductivity.

MPS-2 ceramic discs: The water potential of demineralized water in the ceramic discs (black dotted line) represents the reference matric potential for all samples. We tested the extracts of the samples A (silt), B (sand), F (clay), K (humus), and a saline solution for comparison. The osmotic potential of a sample, i.e., of its extract, is the difference between water potential and reference matric potential.

Soil samples: The colored vertical arrows indicate the water content of selected soil samples (A, B, F, and K) for the range where our equations can be applied. For these ranges of water content, the magnitude of the osmotic potential can be estimated visually. For the application range of our equations, the water content of the humus sample K lies slightly outside of the range that we used in the ceramic specific tests. Therefore, the osmotic potential of sample K can be estimated only by extrapolation. Additional information for the tested soil samples is given in Table 1.



Supplemental Figure S5: Deviation between the soil matric potential from 15 *MPS-2* sensors manufactured in three different years and the reference soil water potential from a dewpoint potentiometer (*WP4C*). The *MPS-2* sensors are color coded according to the year of manufacture (five per year). All measurements were done using soil sample D (Table 1). The vertical dot-dashed line shows the lower application limit of the equations (–4000 kPa). The measurements from one 2014 *MPS-2* sensor (lowermost black line) were considered outliers. For the correction range between around –500 and –4000 kPa (*WP4C* values), the variation coefficient (CV) of the remaining 14 *MPS-2* sensors was 15–20% (mean 17%) at the four water potential levels considered. All measurements were made at the reference temperature of 22°C.



Supplemental Figure S6: Plot of predicted and residual pF values of the regressions (Eq. 2, Table 2). Each color represents a soil group according to Table 1. Each point represents a pF value averaged from five *MPS-2* sensors (independent variable) and four *WP4C* potentiometer measurements (dependent variable) per soil sample and soil water potential level. The range between the black vertical lines corresponds to the proposed application range of the equations. All values refer to the reference temperature of 22°C.