Comparison of soil water potential sensors: a drying experiment

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Impact statement

In situ water retention curve observation is key to capturing the dynamics of root zone functions.

In a drying experiment in a fully controlled environment, we compared the ability of water potential probes to cover a wide range of water potential levels.

We assessed the consistency of the probes and their ability to capture an *in situ* retention curve.

Abstract

The soil water retention curve (WRC) plays a major role in soil's hydrodynamic behaviour. Many measurement techniques are currently available for determining WRC in the laboratory. Direct *in situ* WRC can be obtained from simultaneous soil moisture and water potential readings covering a wide tension range, from saturation to wilting point. There are many widely used soil moisture probes. Whereas near-saturation tension can be measured using water-filled tensiometers, wider ranges of water potential require new, more expensive and less widely used probes. This paper reports on a comparison of three types of soil water potential sensors that could allow us to measure water potential in the field, with a range relevant to water uptake by plants. Polymer tensiometers (POTs), MPS-2 probes and pF-meters were compared, in a controlled drying experiment. The study showed that the POTs and MPS-2 probes had good reliability in their respective range. Combined with a soil moisture probe, these two sensors can provide observed WRCs. The pF-meters below -30 kPa were inaccurate and their response was sensitive to measurement interval, with greater estimated suction at shorter measurement intervals. Recommendations are provided for future tests. *In situ*-WRC can provide supplementary information, particularly with regard to its spatial and temporal variability. It could also improve the results of other measurement techniques, such as geophysical observations.

Keywords

Water retention curve, water potential, soil moisture, probe

Introduction

Knowledge of the soil water retention curve (WRC) is important in order to quantify water flow in such areas as hydrology, soil science and crop production. The soil WRC determines the amount of plant-available water and the energy cost to the plant in taking up water from the soil (Minasny and McBratney, 2003). Combined with the conductivity curve, the soil WRC is used for a direct solution of Richards' equation.

There are currently many measurement techniques for quantifying the soil WRC by recording soil water content and soil water potential (Campbell et al., 1991). In the laboratory, hanging water columns and pressure plate apparatus are commonly used. Multi-step outflow methods are also frequently used, but they have a practical limitation of –100 kPa (Stolte, 1994). Other set-ups include evaporation experiments (Schelle et al., 2013; Schindler et al., 2012; Zhang et al., 2009), freezing apparatus (Bittelli and Flury, 2009) and vapour sorption analysis (Arthur et al., 2013). Laboratory techniques are useful for determining the soil WRC and have been used to demonstrate the impact of hysteresis (Abbasi et al., 2012). Spatiotemporal variability resulting from interactions between physical and biological factors, such as increased porosity induced by root turnover, soil aggregation, biota-induced macropores or specific management effects (Strudley et al., 2008), however, cannot be quantified satisfactorily in static set-ups in the laboratory. In order to be able to quantify the influence of soil heterogeneity and spatiotemporal dynamics on the soil WRC, an *in situ* approach combining soil moisture and soil water potential measurements can provide useful data. Such an approach requires sensors that can measure a representative part of the soil WRC.

There are several techniques for measuring the soil water content part of the in-situ WRC. The volumetric soil water content is often derived by using time domain reflectometry (TDR). This technique has gained widespread acceptance as a standard technique for volumetric water content estimation (Černý, 2009; Chandler et al., 2004; Ferré et al., 2002). Many papers have been written since the introduction of TDR in soil science in the 1970s (Robinson et al., 2003; Topp et al., 2003). Cheaper sensors, such as capacitance probes, have now become an attractive alternative to TDR and are easy to operate (Vereecken et al., 2014).

For the soil water potential part of the in situ WRC, it is more challenging to find sensors with a representative range. To measure soil water potential, water-filled tensiometers are the most commonly used instruments (Whalley et al., 2013), but their measurement range is limited to matric potentials greater than saturation vapor pressure minus atmospheric pressure (Tarantino and Mongiovì, 2001). Conversely, thermocouple psychrometers have poor resolution for wet soils (Scanlon et al., 2003) and heat dissipation sensors have limited functionality near field capacity (Caldwell et al., 2013). In addition, this last method is not derived from thermodynamic principles, but relies on calibrating sensor properties against known soil water potential values (Reece, 1996). Recently, several new sensors for use under *in situ* conditions have been proposed for covering a wider range of matric potentials. Polymer tensiometers (POTs) (De Rooij et al., 2009) extend the range of measurement to wilting point (~1500 kPa), but they are still costly. Other probes, such as MPS (Decagon Devices, Pullman, WA) and pF-meter (Ecotech/Stevenswater) probes, rely on different measurement principles (see 'Materials and methods') and deserve further analysis in order to ensure the correct application of their readings.

There is currently limited information on the performance of new probes. The first release of the MPS probe was tested by Malazian et al. (2011), who concluded that there was good consistency among the probes after local calibration and low temperature effect. POTs were compared with matric potentials converted from water content estimates from TDR data using retention characteristics (Van Der Ploeg et al., 2010). They showed good agreement until the TDR data became too noisy at low water content levels. No specific testing of the pF-meter has yet been reported. So far as we know, the POT, MPS-2 and pF-meter sensors have not been compared in a single experiment. In this paper, we discuss the principles behind each measurement technique, describe a controlled experiment comparing two MPS, two pF-meter and two POT sensors in the same repacked soil and discuss the advantages and disadvantages of each method. A Campbell Scientific CS616 volumetric water content probe was installed in order to build WRCs *in situ* based on potential and water content simultaneous readings. We compared the WRCs with a laboratory-measured WRC.

Materials and methods

Matric potential sensors

MPS sensors (Decagon Devices, Inc. Pullman, USA) use a porous ceramic disc and pF-meters (ecoTech Umwelt-Meßsysteme GmbH Bonn, Germany) use a porous ceramic cone. When in contact with soil, the water potential in the disc or cone equilibrates with the water potential of the surrounding soil. Neither sensor measures the water potential in the ceramic disc or cone directly, but infers it from measuring another property and a factory calibration curve.

The MPS-2 sensor (Decagon Devices, Inc.) consists of two porous ceramic plates surrounded by two perforated steel plates. According to the manufacturer, the porous ceramics have a wide pore size distribution. The measurement itself involves a capacitive reading of the dielectric permittivity of the ceramic disc. A factory calibration using the relationship between capacitance and dielectric permittivity of the disc gives the dielectric permittivity. The latter is converted into water content, which is then converted into a potential using the ceramic WRC (Kizito et al., 2008; Malazian et al., 2011). The measurement ranges from -10 kPa to -500 kPa. Currently, the MPS-2 sensor is calibrated at two points. The new release of this probe, the MPS-

6, is calibrated at six points, increasing its accuracy from 25% to 10%, respectively, in the range of -10 to -100 kPa.

In the first and second release of the pF-meter (ecotech Umwelt-Meßsysteme GmbH Bonn), the porous ceramic cone is 1 cm and 2.5 cm, respectively. The measurement involves measuring the heat capacity of the cone after a heat pulse. The heat capacity varies in relation to the water content in the cone, and so captures the soil water potential when the ceramic is in equilibrium with the surrounding soil. A factory calibration allows the user to get direct readings of the pF value (Ecotech, 2010). The measurement ranges from pF 0 to pF 7. In this study, we used two pF-meters released at different times, the one tested by Zhang et al. (2009) and the 2010 version described by Ecotech (2010). Zhang et al. (2009) reported satisfactory results with the first release, but they used it as stand-alone sensor in their experiment, without assessing its reliability. The differences between the two releases were not detailed by the manufacturer, but at least the ceramic cones were different in shape and size.

POTs consist of a solid ceramic cone with an air entry value that exceeds the measurement range of interest (–1.83 [α-Al2O3 cone] and –117 MPa [γ-Al2O3 ceramic membrane] at a water surface tension of 0.073 Nm^{-1}, a water density of 998 kgm^{-3} and 20°C) and a small chamber (<1 mm depth) filled with Praestol 2500 polymer. During construction (see Bakker et al., 2007 and Van Der Ploeg et al., 2010 for details), the tensiometer is filled with dry hydrophilic polymer. Once immerged in water, the polymer absorbs the water and develops an internal hydrostatic pressure recorded by a pressure transducer. When placed in soil, equilibrium between soil potential and ceramic cone potential is achieved as water leaves the chamber, reducing the internal pressure. The polymer solution and, to a lesser extent, the sensor's body are temperature sensitive, and therefore a temperature sensor (0-40°C, accuracy 0.01°C) is included (Bakker et al., 2007). Processing the readings includes a temperature compensation that uses a linear relationship between pressure and temperature. This relationship is established for each probe. The pressure transducer has a range of between 2.201 and −0.175 MPa, with an accuracy of 2.38×10^{-3} MPa (0.1% of the full scale). The POT measurements range from 0 to −1.6 MPa at 25°C.

Soil water content sensors

The CS-616 probe reads the relative dielectric permittivity of soil based on the frequency with which successive pulses can be sent along the rods and come back. Due to the high permittivity of water, this frequency is considerably lower in humid soils. The output frequency of the probe or the related period can provide the water content using factory calibration. The CS-616 has demonstrated some temperature sensitivity, however, which can partially be compensated (Varble and Chávez, 2011). According to Mittelbach et al. (2012), temperature effect on CS-616 can be partially corrected using equation (1) applied on raw data:

$$Period\_C = period + (20 - T).(0.526 - 0.052\, period + 0.00136\, period^2) \quad [1]$$

where *Period_C* is the corrected raw data, *period* is the raw data, *T* is the temperature in °C. It is important to note that this correction remains relevant even under controlled conditions because the reference temperature for sensor calibration is 20°C (Mittelbach et al., 2012). In this study, the temperature recorded by the POTs was used for correction. It varied between 15°C and 16.5°C in our experiment. Equation (2) gives the calibration equation used to derive volumetric water content:

$$\theta = 0.0007\, period\_C^2 - 0.0063\, period\_C - 0.0663 \quad [2]$$

where θ is the volumetric water content [cm^3/cm^3]. It is well established that a soil-specific calibration can improve reading accuracy (Kinzli et al., 2012). It has also been shown, however, that standard equations perform well for soils with low organic carbon content (Vaz et al., 2013).

Table 1 presents the measurement range, accuracy and resolution of the probes as provided by the manufacturers.

Experimental setup

Two millimetre sieved air-dried loamy soil (10.9% clay, 57.2% silt, 31.9% sand) was repacked uniformly in a cylindrical ring (diameter 47.5 cm, height 10 cm) with a perforated base. The soil organic carbon content was 3.18%. We added the soil in increments of 2 cm. After each layer, we compacted it and then roughened the surface before adding a new layer. The density of the repacked soil was 1.37 $kg.dm^{-3}$. At mid-height (5 cm), we installed the sensors, following the manufacturers' recommendations. The MPS-2 probes were packed in a wet loamy soil to ensure good contact between the ceramic and the soil. The pF-meters were put into water for 30 s and then handled vertically and placed diagonally in the soil in order to prevent water blocking the ventilation tube. The POTs and CS-616 probes were placed horizontally. All the sensing parts of the sensors were therefore at the same height in the soil, between 4 and 6 cm above the ring's base. Mohrath et al. (1997) demonstrated that such a slight variation in position would not affect WRC measurements in an evaporation experiment. This was also confirmed by Hydrus modelling of the experiment (data not shown). The packing continued in order to fill the ring completely and ensure that more than 2.5 cm of soil covered the CS-616 rods, so that its measurement volume associated with the electromagnetic field intensity was completely below the soil surface.

The soil was then saturated from the bottom by placing the ring in a larger watertight container and adding non-chlorinated tap water progressively over 2 days. The ring was then left to saturate for 2 more days to guarantee stable readings from all the probes. At the end of these 4 days of saturation, the secondary container was drained and the soil began to dry. The whole experiment took place in a temperature-controlled room with a temperature of 16ºC [+/- 1 ºC]. An air dryer was switched on in order to reduce the relative humidity to about 40% in the room and maintain a smooth evaporation rate. The measurement interval for all the probes was set at 15 min. It took 70 days to evaporate about 7 litres of water and reach the end of the experiment.

After drying, five intact soil cores (5 cm in diameter, 5 cm high) were sampled between the probes in the ring. They were saturated from the bottom and a reference WRC was established using a sand box (between 0 and -9.8 kPa), suction plates (between -9.8 and -59 kPa) and measurements of disturbed samples with pressure plates (-100 and -1,500 kPa).

Two complementary tests using the second release of the pF-meter appeared to be necessary. The first one consisted in installing the sensor in 2 mm sieved loamy soil with a potential close to -1000 kPa. We packed the set-up in a plastic film in order to avoid change in water content and we tested 3 measurement intervals (15, 30, 60 minutes). The second one consisted in putting the sensor in a closed chamber above 0.2M KCl solution at 20°C (Scanlon et al., 2002) in order to check the its reliability in dry range.

Data treatment

The consistency of the sensor readings was analysed for each sensor type. Coefficients of linear regression between both sensors of the same type and correlation coefficients were determined. The sensor types were then compared. The observed WRCs obtained by plotting the matric head readings of the POT, MPS and pF-meter probes against CS-616 were compared with the reference WRC, as was done by Van Der Ploeg et al. (2010).

Results and discussion

Temporal analysis

Figure 1 presents the readings of the matric head sensors over time, as well as the volumetric water content read by the CS-616 probe. It shows that the evaporation rate was even during the experiment, with a slight decrease at the end, as would be expected from a loamy soil (Idso et al., 1974). Due to technical issues, there was a short interruption in the records on about the 55th day for the first release of the pF-meter (which was connected to a specific data logger) and the 58th day for the second release of the pF-meter and both MPS-2 probes (which were connected to another data logger). POTs are stand-alone devices with their own power and data storage systems.

The MPS-2 probes started to respond to the soil water potential at -20 to -30kPa, whereas the other probes gave readings throughout the evaporation experiment. This is consistent with the measurement range provided, albeit a little narrower. It also resembles the observations reported by Malazian et al. (2011) in their analysis of the first release of the MPS probe. The later reaction to matric potential change in the wet range could be related to the lower air entry point of the probe's ceramic. Since the range of MPS probes is limited to -500 kPa by the provider, readings below this value were not considered in our study.

Probes comparison

The two POTs showed a high consistency level, with a linear regression close to the 1:1 line and a determination coefficient exceeding 0.99 (Fig. 2). The residuals were not randomly distributed around zero, however, which indicated that there was some systematic bias between the sensors (Fig. 2).

Using the segmented package (Muggeo and Adelfio, 2011), we identified a breakpoint around -400 kPa. When considering this breakpoint in a broken line adjustment, the consistency of the POTs appeared remarkable. Between 0 and -400 kPa, the slope coefficient was 0.76, and between -400 and -1500 kPa it was 1.20. This breakpoint could be due to differences between the POTs or it might suggest an influence of the non-continuity of the aqueous phase in the drying soil, or between the POT and the soil, on the POT readings. This needs to be confirmed with other POTs as it was beyond the scope of this study.

Figure 3 shows the comparison between the MPS-2 probes. The probes are quite consistent with each other in the -20 to -500 kPa range. They show a correlation coefficient close to 1 with a regression line close to the 1:1 line, even though the slope coefficient is a bit lower than 1 (0.86). This value indicates that the differences between the probes are about 15%, which may lead to non-negligible differences in drier situations. Some oscillations were observed for one of the probes in a limited number of readings.

Figure 4 shows the comparison between the averaged values of the POT readings and the MPS-2 readings. The comparison is presented in the measurement range of the MPS-2, which is narrower than the POT range. The determination coefficient remained greater than 0.96, but the slope coefficient was close to 1.3, suggesting that, below -200 kPa, MPS-2 probes have a maximum potential difference of 30% compared with POTs in their range. The graph actually shows a curvature and the discrepancy increases with decreasing potential.

For both pF-meter sensors, a comparison such as that conducted for the POT and MPS-2 probes was not meaningful because they showed strongly diverging data (see Fig 1). In the following discussions, only the second release of the pF-meter sensor is compared with the other probes.

The observed tensions from the POT, MPS-2 and pF-meter probes were plotted against the volumetric water content taken by the CS-616 probe in order to draw the WRCs in Figure 5. The figure also shows the reference WRC obtained from five undisturbed soil samples taken from the cylindrical ring after the experiment. The whiskers show the standard deviation. Comparing the reference WRC and CS-616, it is likely that the CS-616 slightly underestimated the soil moisture at the start of our experiment. The temperature correction proposed by Mittelbach et al. (2012) is known to compensate for the temperature deviation of the CS-616 probe only partially, particularly in wet soils. This seemed to be confirmed in our study. Another option could be that there were slight differences in the saturation procedure between the cylindrical ring in the experiment and those used to measure the reference WRC, despite having followed a similar procedure. These differences could also derive from the comparison between the probe readings and the reference WRC obtained from the small intact cores. The manual repacking of soil can lead to small heterogeneities in bulk density. In our case, this seems to be limited because we measured a mean bulk density of 1.37 g.cm^{-3} in our intact cores, with a standard deviation of 0.03g.cm^{-3}. Te Brake et al. (2013) reported that 300 mm CS-616 probes installed in the field showed an earlier drop in water content than 56 mm EC5 probes, which was attributed to the inclusion of more heterogeneities in the larger CS-616 measurement volume. In addition, the factory calibration for the CS-616 probe may underestimate moisture content. Despite our attempt to wet the soil ring with the instruments in the same manner used for the soil cores taken from the ring, the larger volume and height of the soil ring might have retained more soil air. Both effects affected the wet end of the curve mainly. Between -5 and -100 kPa, the reference WRC corresponds very well to the observed ones, except for the WRC based on pF-meter readings.

Although the CS-616 data were not completely corrected in terms of temperature effects, they affected all the WRCs in the same way and we can therefore compare them. The POT and pF-meter sensors have wider measurement ranges. The MPS-2 sensors are more limited, as noted earlier. The pF-meter diverged from the other probes after -50 kPa during the drying process and strongly underestimated the water tension in the remainder of the experiment.

Among the possible causes of the poor performance of the pF-meter, we question the measurement interval used, which may have been too short to allow a complete cooling of the ceramic and surrounding soil, particularly in dryer context. The 15 minutes interval was set as it was the minimum interval between two readings recommended by the providers. But after the technical failure of the first release, the time-step was erroneously set to one hour instead of 15 minutes. The 1 h measurement interval lasted for 9 h and was then restored to 15 min. Even if the first release of the pF-meter yielded erroneous results, the data recorded using different measurement intervals (figure 1) lead us to test the impact of this interval using the second release of the pF-meter. The figure 6 shows that it responded in the same manner as the first release, with respect to the measurement interval, yielding lower suctions with longer measurement interval. The explanation of this misbehaviour is not easy to formulate since technical details about how the probe is functioning are lacking. The measurement of the potential with the pF-meter (second release) in equilibrium with 0.2M KCl solution, using a 15 minutes measurement interval, overestimated the suction by 20 % (reading -1071kPa instead of -891kPa). This needs to be confirmed and could favour the use of pF-meters in particular situations where the soil remains quite wet and where long time-steps are acceptable. The strong differences between the two releases, however, raise other questions. Shape and surface/volume ratio of the ceramic changed between both releases, but because we had only one piece of each sensor, and because technical changes between both releases were not available, we were unable to draw further conclusions.

With regard to the MPS-2 sensors, they performed very well in their range. The overestimation of the tension had a minor effect on the WRCs, as a result of the log scale (Figure 5). Finally, it was clear that the POTs were noisy close to saturation, and this behaviour was enhanced by the log scale. Below -10 kPa, the noise almost disappeared and the probes measured continuously until the end of the experiment. The last point of the reference WRC remained a little higher than the probes' readings. This might be due to probe calibration issues or to the difficulties in reaching equilibrium in very dry conditions with the pressure plates (Cresswell et al., 2008).

Conclusions

The objective of this paper was to compare three water potential probes and their ability to capture the WRC of a given soil sample from saturation to wilting point. Further tests need to be done in order to assess the reliability of these probes for a wetting period. We worked under controlled laboratory conditions, with controlled temperature and air humidity and with a mineral loamy soil. The MPS-2 probes performed very well in these conditions, even though they had a narrower measuring range than the two other devices. The fact that these probes do not capture the wet end of the WRC might be a major drawback as the wet end of the retention curve cannot be met properly when data is missing in that range. We recommend that further tests under field conditions be conducted in order to assess the temperature dependence, but our study indicated that the MPS-2 probe is a relatively cheap and promising sensor. The MPS2 sensor also delivers temperature with an accuracy of 0.1 °C, which is sufficient for the temperature correction of the CS-616

The POTs performed very well and covered the targeted range. They are known to be temperature sensitive, and the data treatment therefore included temperature compensation. The temperature compensation also permits them to be used under field conditions.

The MPS-2 and POT probes, combined with a CS-616 soil moisture sensor, were able to capture the *in situ* WRC. Our experiment was designed to observe the slow and continuous drying of soil in order to be able to make a comparison with a reference WRC. The combination of tension and soil moisture probes in the field opens the way for observing the changing conditions of WRCs as a result of dynamic vadose zone processes. In this context, we recommend completing the instrumentation with a temperature probe in order to apply adequate correction to soil moisture readings. The pF-meter (second release) provided good results with fairly wet soils, but was inaccurate above a tension of 30 kPa. Furthermore, it was sensitive to the measurement interval. The physics behind these observations remain unclear.

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Table 1. Range, resolution and accuracy of the probes, according to the providers.

Sensor	Range	Accuracy	Resolution
MPS-2	-10 to -500 kPa	±25% between -5 and -100 kPa	0.1 kPa
pF-meter new release	0 to -1000000 kPa	Not available	0.01 pF unit
pF-meter old release	0 to -1000000 kPa	Not available	0.01 pF unit
POT	0 to -1600 kPa	0.1% Full Scale	0.05 kPa
CS616	0 to 50% VWC	±2.5% VWC	0.1% VWC

Figure 1: Temporal evolution of the probe readings during the evaporation experiment. Soil water potential probes MPS-2, pF-meter (15 minutes measurement interval) and POT refer to the left scale; the green dots present the readings of the CS-616 soil moisture probe and refer to the right scale.

Figure 2: Readings of the polymer tensiometers (POTs). On the upper graph, the black dots represent the readings, the dotted grey line shows the 1:1 line and the red line shows the linear regression between the readings of the two probes. The lower graph shows the residual analysis of the POTs linear regression

Figure 3: Comparison of the MPS-2 probes in the -500 to -20 kPa range

Figure 4: Comparison between POT and MPS-2 probes

Figure 5: Comparison between *in situ* and reference water retention curves (WRCs). The whiskers show the standard deviation of the water content measured in the five intact cores. The pF-meter measurement interval was 15 minutes.

Figure 6: Effect of the measurement interval on pFmeter R2 readings. The soil water content remained unchanged during the experiment. The arrows show the duration of the periods and the measurement interval used during each of them.

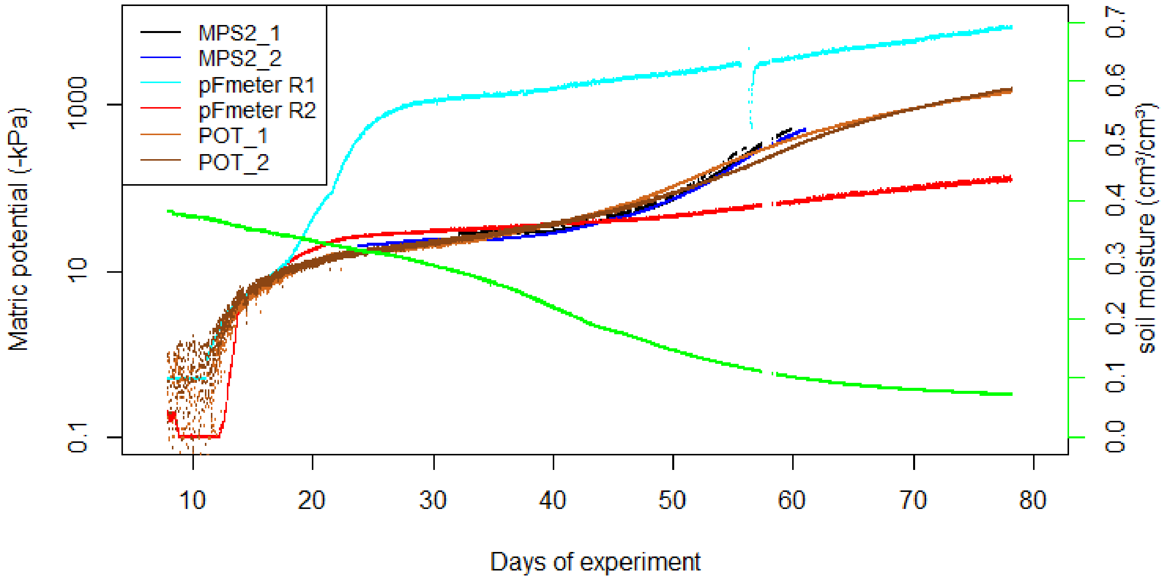


Figure 3 : Temporal evolution of the probe readings during the evaporation experiment. Soil water potential probes MPS-2, pF-meter(15 minutes measurement interval) and POT refer to the left scale; the green dots present the readings of the CS-616 soil moisture probe and refer to the right scale.

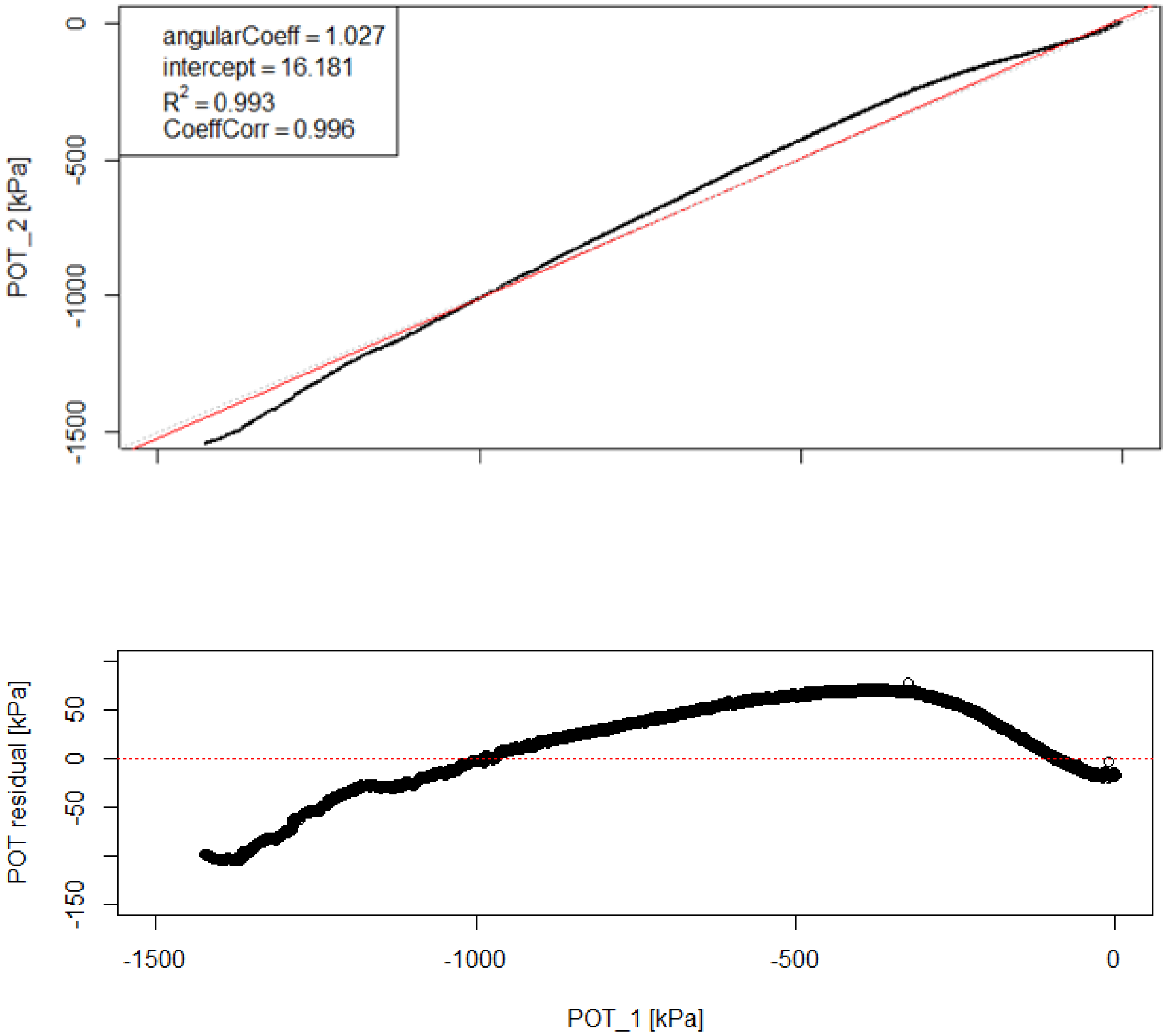
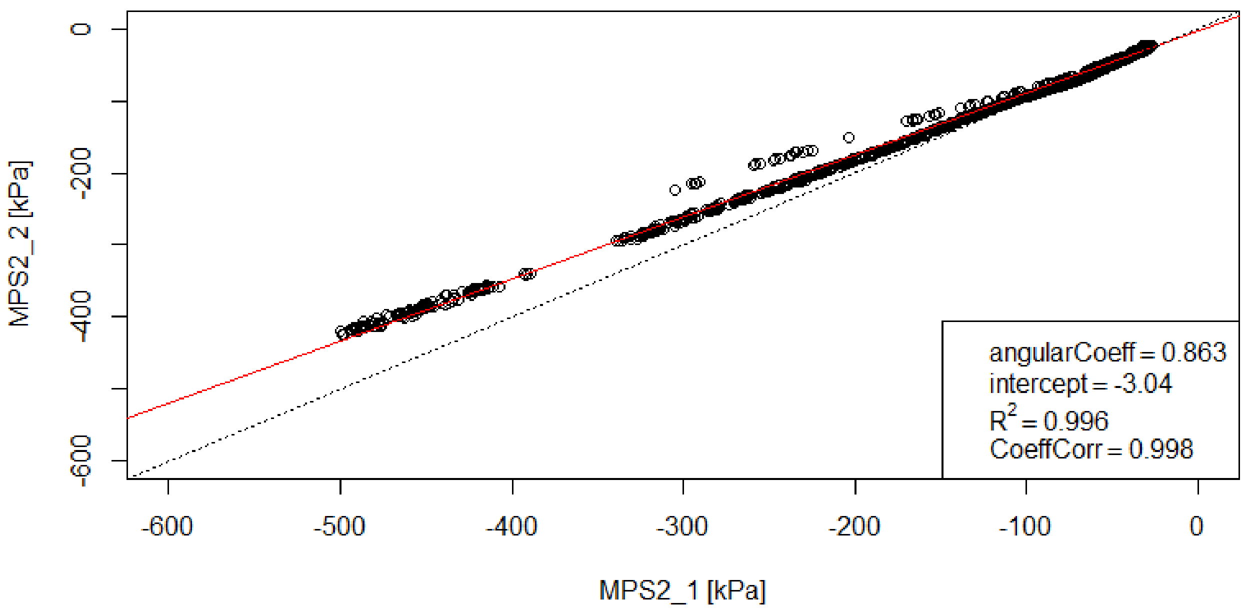


Figure 4: Readings of the polymer tensiometers (POTs). On the upper graph, the black dots represent the readings, the dotted grey line shows the 1:1 line and the red line shows the linear regression between the readings of the two probes. The lower graph shows the residual analysis of the POTs linear regression



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468 **Figure 3 : Comparison of the MPS-2 probes in the -500 to -20 kPa range**

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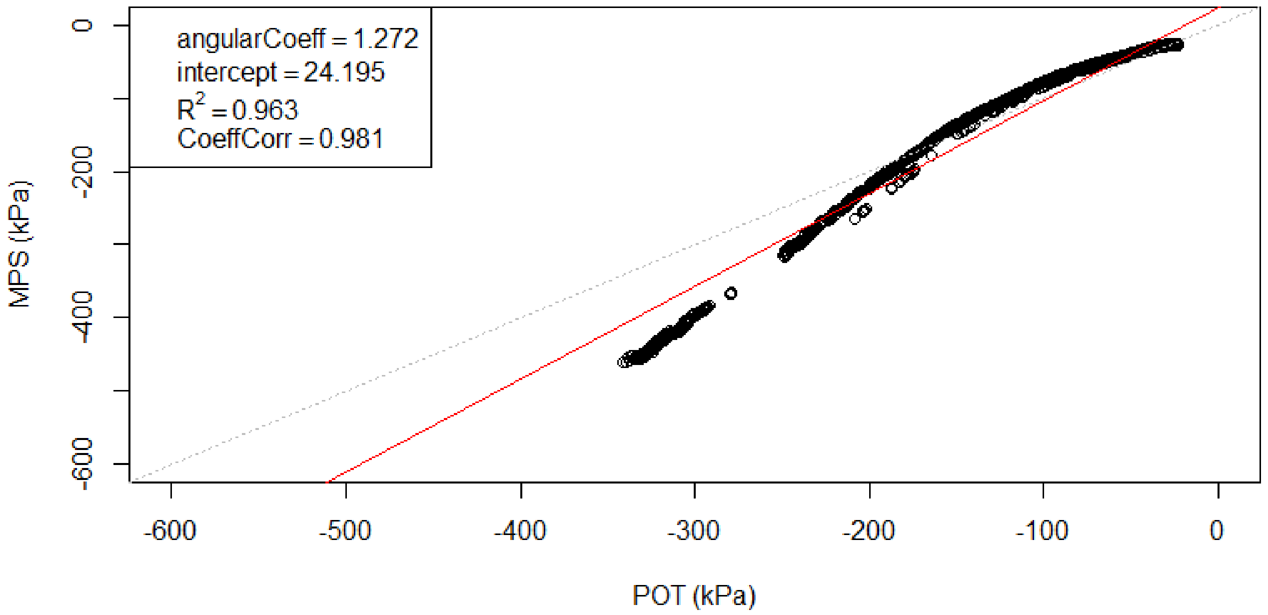


Figure 4 : Comparison between POT and MPS-2 probes

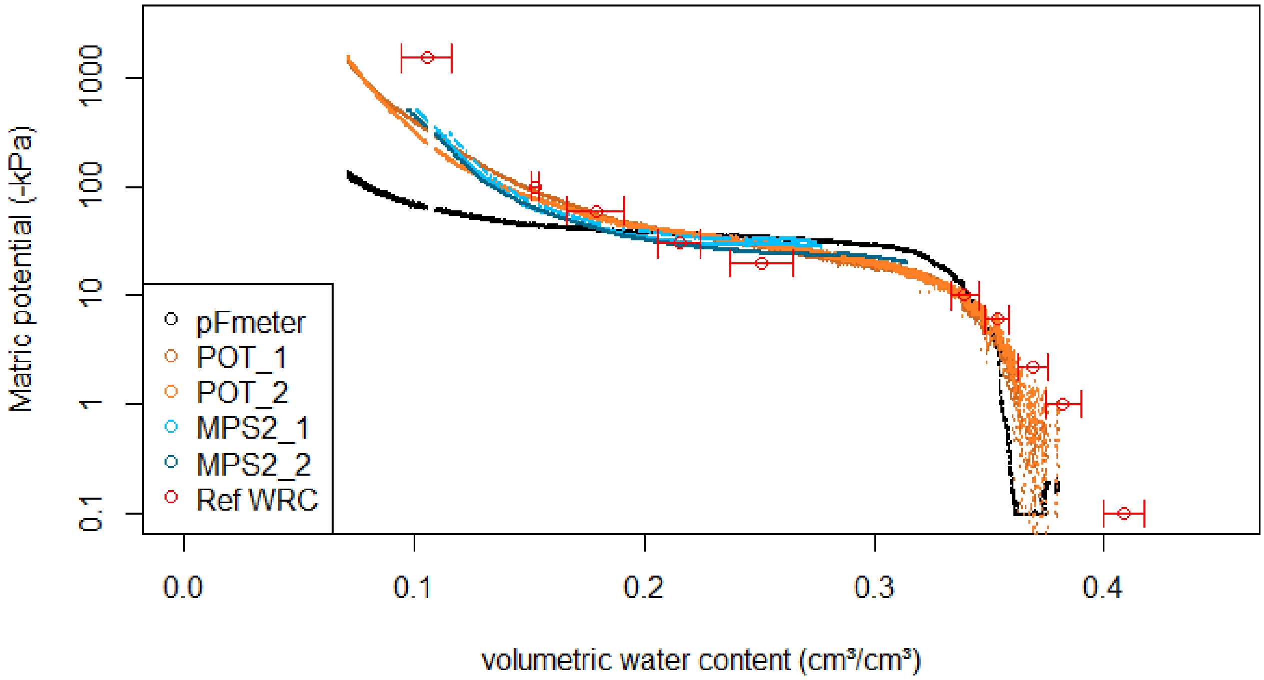
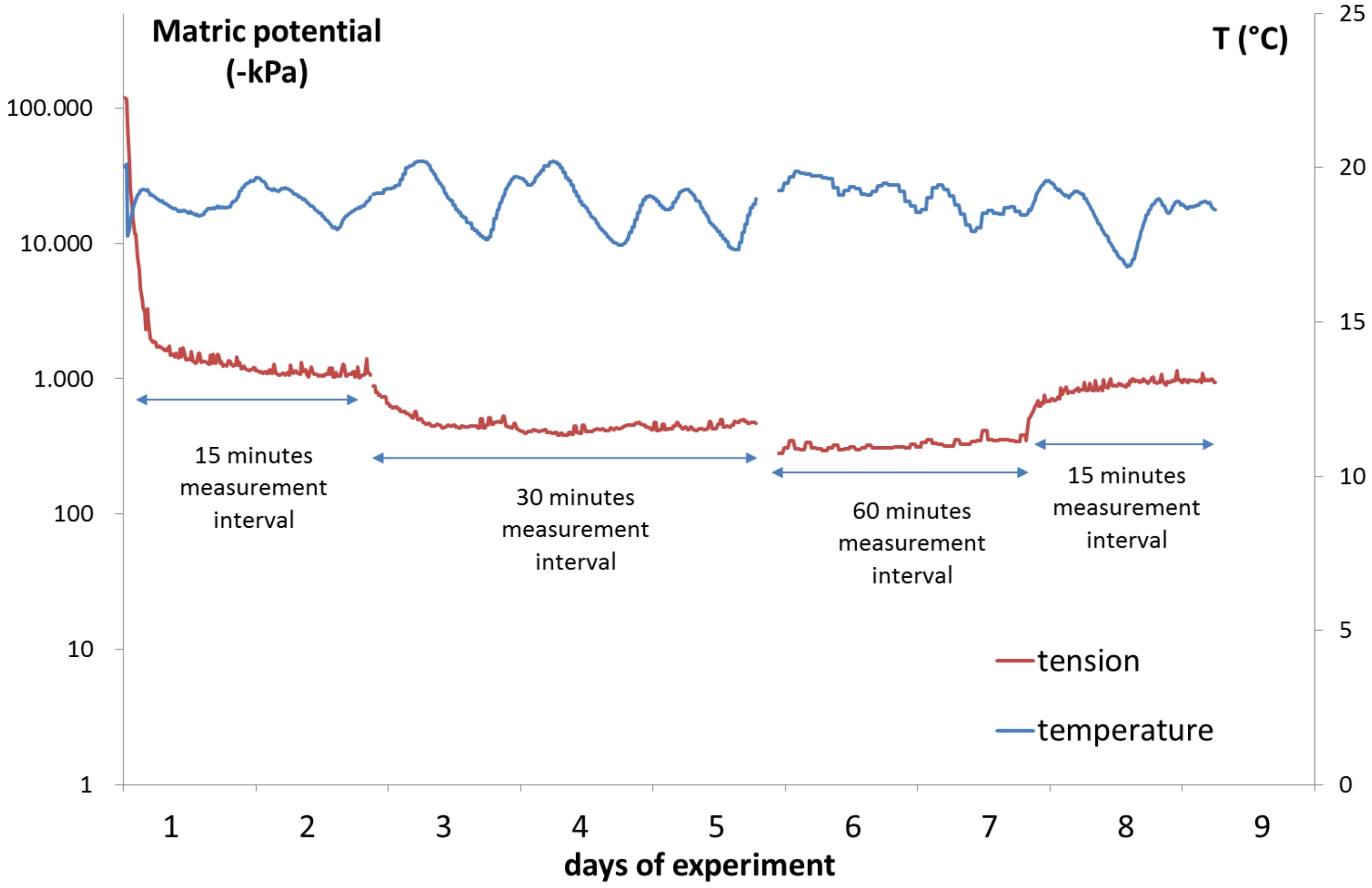


Figure 5 : Comparison between *in situ* and reference water retention curves (WRCs). The whiskers show the standard deviation of the water content measured in the five intact cores. . The pF-meter measurement interval was 15 minutes.



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