Measuring Soil Water Potential Using Dielectric Permittivity and Porous Ceramic

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Abstract. ***Irrigation control systems incorporating soils measurements to make "smart" decisions have not fully embraced soil moisture sensors because of difficulties associated with data interpretation. While soil water potential data are easier to interpret than soil volumetric water content data, the lack of a robust and inexpensive soil water potential sensor has prevented the irrigation industry from using water potential to control irrigation. The goal of our research was to develop a low cost, simple, and accurate water potential sensor that is easy to install and long-lasting in the ground. The water potential sensor (WPS) that we developed measured the dielectric permittivity of a well-characterized porous ceramic disc in equilibrium with the surrounding soil. We evaluated sensor performance over a wide range of water potentials using tensiometers and pressure plates. Sensor calibration showed high measurement sensitivity in range of soil water potentials that plants grow. In addition, confounding environmental factors like soil electrical conductivity and soil type did not appear to affect sensor output. Results suggest the WPS is a tool that makes irrigation scheduling as simple as regulating heating in a home.***

Keywords. Soil moisture, water potential, soil moisture sensor, smart irrigation

Introduction

"Smart" irrigation control is critical to conserving municipal water supplies. Among many control strategies, soil moisture monitoring has become one of the more promising irrigation control technologies because the measurement provides information about the availability of water in the soil (Campbell and Campbell, 1982). However, the majority of soil moisture technologies only determine the amount of water in the soil, not if irrigation is necessary. That decision is left to the user. Because most people do not know how to interpret soil moisture measurements, general integration of these devices into irrigation control systems has been slow.

The effects of soil particle size and soil density are at the heart of the challenge of interpreting soil moisture measurements. The size distribution of the particles in soil determines if water will be available to plant growth. The smaller the majority of the particles, the more tightly water is bound. Thus, a sand-sized soil and a clay-sized soil with the same amount of water in them will have completely different amounts of water available to the plant. For example, sand with 20% water by volume (VWC) may only bind 5% (by volume) tightly so 15% is freely available for uptake and use in biochemical processes and transpiration. A clay with 20% water by volume will exhibit completely different behavior. In this case, the water will be bound so tightly by the extensive surface area of the fine particles that 0% will be freely available and most plants will find it difficult or impossible to remove any water at all. Clearly, simply relying on the amount of water to determine the needs of the plant can lead to gross interpretation errors.

Ideally, the solution to "smart" irrigation control is similar to placing a thermostat in a house; people with no knowledge of thermoregulation can easily use their thermostat to keep their homes at a comfortable temperature. Instead, most irrigation control systems that integrating soil moisture measurements use an arbitrary "refill" point, set by the user, to make irrigation decisions. This is an imprecise technique, often relying on the knowledge of the user to define the level of soil moisture plants require. In fact, plant water requirements are better defined by a parameter called "soil water potential" (SWP) which defines the energy state, not the amount, of water in soil. Plants use a gradient in water potential to draw or literally suck water from the soil. Since healthy plants require a well defined range of water potentials for optimum growth, much the way people have a set range of temperatures for comfort, a SWP sensor could control irrigation with minimal knowledge of irrigation requirements.

Differences in water potential between the atmosphere and soils drive water movement from the soil through the plants and into the atmosphere. Water will always move from high water potential (less negative) to low water potential (more negative). However, if this gradient becomes too high (because of lack of soil moisture), plants can no longer pull water from the soil. The point at which the water potential is below optimal levels is typically < -100 kPa. This relationship is independent of soil type, and the optimal SWP growth ranges for specific plants are well tabulated in scientific literature.

Although SWP sensors have been available for many years, currently available sensors are either inaccurate, too expensive, or have short field life (Scanlon et al., 2002). The objective of this study was to design a low cost, high quality sensor to measure SWP *in situ*. To meet our goals, the sensor will show no soil type dependence, work over a wide range of SWP, have low salinity response, and agree well with existing technologies.

Sensor Design

When a porous material (ceramic) is put in contact with the soil, water will flow into or out of that material until the material's water potential is equal to the soil's water potential. As with any porous material, ceramic has a unique, static relationship between the amount of water in the matrix (water content) and its water potential, called a moisture characteristic. The WPS measures the water potential of the soil by equilibrating a ceramic matrix with the soil, measuring the dielectric permittivity of the ceramic to find its water content, then determining the water potential through the moisture characteristic relationship. Instead of converting the sensor output to dielectric and then water content, correlations are made directly between sensor output and water potential.

Laboratory Calibration and Characterization

1 and 5-bar pressure plates were used to create the moisture characteristic for the WPS. To determine points between 0 and 5 bars, we used a tensiometer for the wet range and a thermocouple psychrometer and a chlled miller hygrometer for the dry range. Sensors were packed into saturated soil on 1 and 5-bar pressure plates and allowed to equilibrate for at least 48 h at a variety of pressures. Two soil textures (sandy loam and silty clay loam) were tested to ensure sensor calibration was constant in differing soil types.

After calibration, sensors were installed in a silt loam together with tensiometers to show relative response time and water potential range. Wheat was grown in the soil under sodium grow lights to simulate field water use conditions.

Sensors were also tested to determine their sensitivity to electrical conductivity. To do this, the ceramic disks were vacuum saturated in solutions with a range of electrical conductivities. Data from the sensors in soils containing different electrical conductivities were not significantly different.

Results and Discussion

A time series of sensor equilibration on a pressure plate over a range of pressures is show in Fig. 1. The stair-step nature of sensor output shows repeated pressure changes and sensor equilibration. Although sensor output did not plateau for more than 24 h in some cases, it is likely that these long equilibration times are due to the equilibration of the entire pressure plate together with the soil and not the sensor themselves.

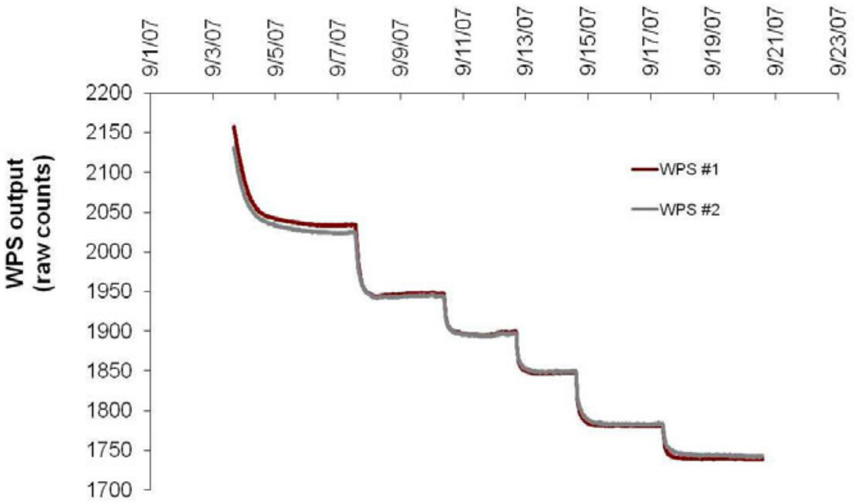

Figure 1. Time-series WPS calibration data collected in silty clay loam soil in 1 bar pressure plate apparatus. Chamber pressure settings are shown at each step.

Sensor calibration data were derived from the equilibrated sensor output at each chamber pressure (see plateau values in Fig. 1). Ideally, the WPS would have the same calibration curve, regardless of soil type. Indeed, Figure 2 (a&b) shows no difference between water potential readings on two different pressure plates and in the two soil types. Especially impressive is the way the calibration lines matchup between the one bar and five bar pressure plates, constituting entirely different measurement systems.

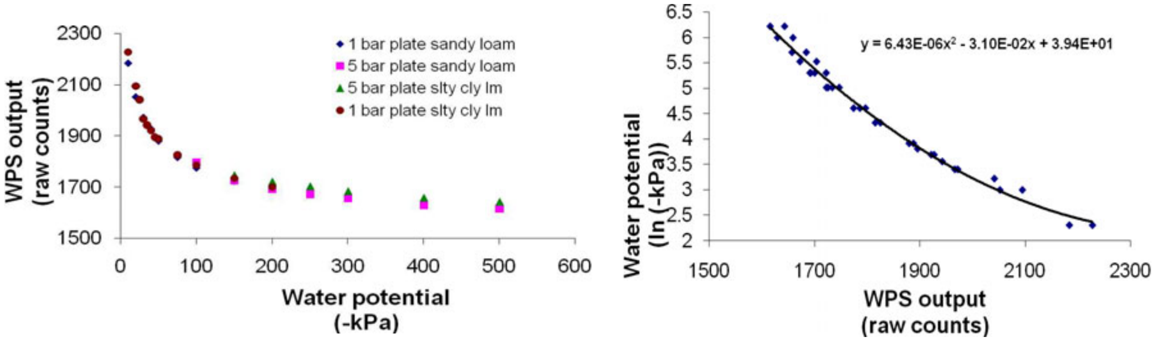

Figure 2. Calibration data collected from the WPS (a) plotted with linear axes and (b) plotted with water potential units in logarithmic increments. The derived calibration function for the semi-log data is shown in the upper right hand corner of Figure 2(b).

Semi-log plots of the calibration data show a quadratic relationship between sensor output and water potential (Figure 2b). The sensors were calibrated from these data, which requires both a natural log transformation and a subsequent quadratic conversion. More importantly, sensor data show high sensitivity in the most important range for actively growing plant, 0 to -100 kPa (1 bar = 100 kPa). However, the data also show the sensor will not measure to complete saturation; it reaches a maximum value at -9 kPa. This maximum is called the air entry potential of the ceramic and represents the potential that water begins to drain from pores in the ceramic matrix. At water potentials closer to zero, the soil will exert a pull on the water to drain the matrix but the binding strength of the ceramic will not allow water to flow out. Although an upper water potential limit closer to zero would be nice, it is not necessary for irrigation control. On the dry end, the WPS will work well down to SWP of approximately -500 kPa. This lower limit is more than adequate for actively growing plants although it does not reach the commonly accepted value for permanent wilting point of -1500 kPa.

Combined WPS and tensiometer data in a silt loam with actively growing wheat are shown in Fig. 3. Data from the WPS agree well across several dry-down events, marking heavy daytime wheat water uptake with steep declines in water potential and nighttime dormancy with plateaus. Response time of the WPS is consistent with the tensiometer, further supporting the hypothesis that long read times in the pressure chamber were due to system and not sensor equilibration. The abrupt end to tensiometer data during the last dry-down was caused by tensiometer cavitation, underscoring the challenges of maintaining that technology in functional condition (Young and Sisson, 2002).

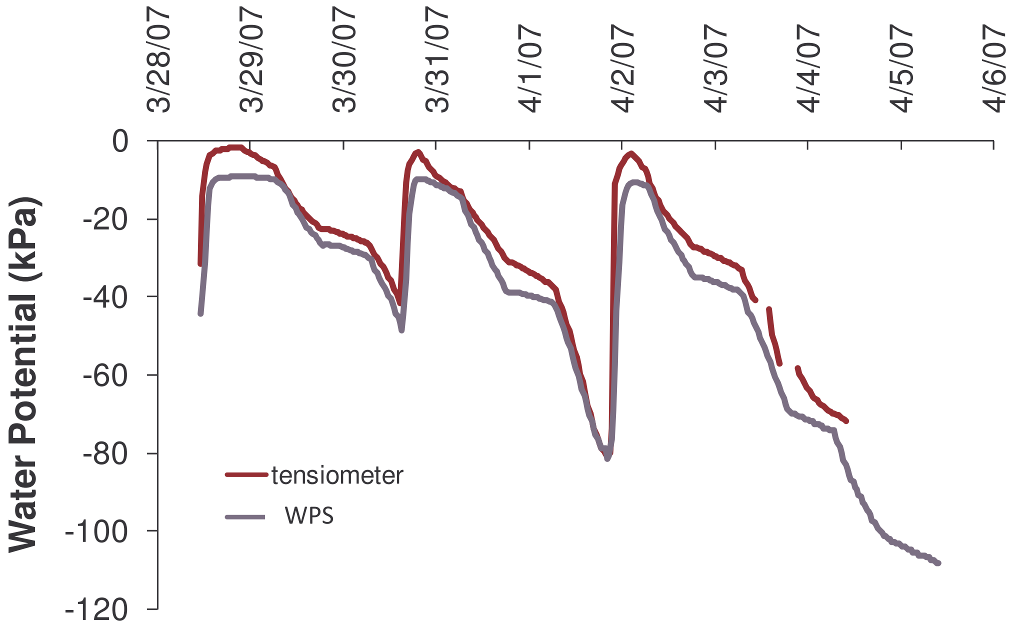

Figure 3. Time-series water potential measured with a calibrated WPS and a tensiometer over several drydown and re-wetting cycles in an agricultural soil under wheat.

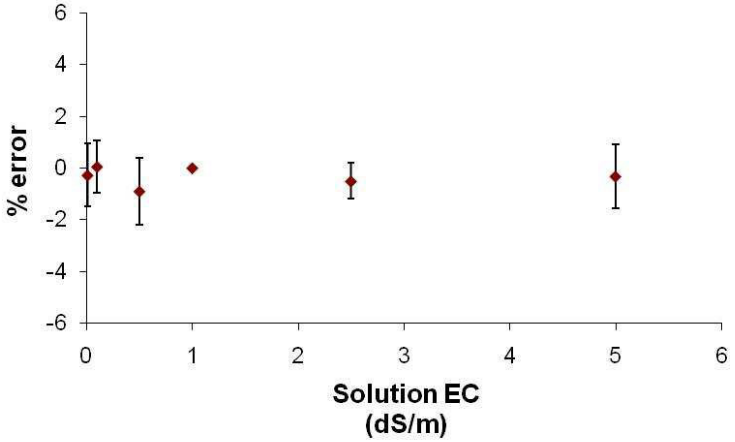

Figure 4. WPS sensitivity to soil solution to electrical conductivity. All values have been normalized to 1 dS/m solution values. Error bars are ±1 standard deviation from a sample of 10 WPS sensors.

Soil salinity did not appear to affect the sensor, changing < 1% over a range of ceramic solution electrical conductivies of 0 to 5 dS m^{-1}. The mechanism for the low sensitivity to salinity is unclear. The sensor's 70 MHz measurement frequency along with its no-contact measurement do reduce salt effects (Kizito et al., 2008). Still, there may be some salinity mitigation from the ceramic as well. With its extensive ability to bind charged ions, the clay ceramic may buffer salt effects by simply binding a portion of the ions in the water, thus reducing their deleterious effects.

Conclusions

The WPS performed well in our tests showing an extensive measurement range, fast equilibration, consistent readings in differing soil types, and low sensitivity to soil salinity. In addition, calibration was consistent between two soil types and with a variety of calibration techniques. Indeed, data suggest that the design objectives for the sensor were met. The broad range of water potential sensitivity will give irrigation controllers complete freedom to use literature values for healthy plants and simply control to an optimum value in the same way thermostats control temperature.

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