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TECHNICAL NOTE

Fundamental Soil Science

Steps toward an integrated soil water tension and osmotic tension sensor

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Abstract

The two most important abiotic plant stressors that impact plant development and crop yields are water stress and salinity stress. These issues are particularly important in arid and semi-arid regions. According to a 2019 research paper, "thirty crop species provide 90% of our food, most of which display severe yield losses under moderate salinity." Moderate salinity is defined as extracted pore-water salinity in the range of 4–8 dS m^{-1}. Currently, commercially available soil moisture and bulk soil electrical conductivity sensors can estimate in situ soil pore-water electrical conductivity with suitably calibrated soil moisture and electrical conductivity models for a wide range of soil types and growing media. With knowledge of the pore-water electrical conductivity it is possible to estimate osmotic tension. Furthermore, there are commercially available dielectric tensiometers that provide soil water tension measurements from the water content of a porous matrix component that is in equilibrium with the water capillary forces in the surrounding soil or growing media. Combining soil moisture and soil water tension measurements enables water retention curves and the hydraulic properties of a soil to be determined. However, the overall ability of a plant to extract water from a soil or substrate is typically dominated by water tension and osmotic tension. Currently, while the technology blocks exist in different commercial offerings, the combination of a water tension and osmotic tension in an integrated sensor does not exist. A key benefit of the porous matrix in a dielectric tensiometer is that electrical measurements include a component of extracted water from the soil or growing media. With the appropriate dielectric characterization of the porous matrix, there should be no need for soil-specific calibrations. The aim of the paper is to outline the measurement processing that could be implemented into an integrated water tension and osmotic tension sensor.

1 | INTRODUCTION

Water stress and salinity stress are the two most important abiotic plant stressors that impact plant development and crop yields in arid and semi-arid regions. Zörb et al. (2019) pointed out that "thirty crop species provide 90% of our food, most of which display severe yield losses under moderate salinity." Moderate salinity is defined as extracted pore-water salinity in the range of 4–8 dS m^{-1}. Plant-available water is determined by soil water tension (soil matric potential) and osmotic tension, and the effect of salinity is a combination of the osmotic tension, the plant's capacity to osmotically adjust, and the specific toxicity of the salt (Sheldon et al., 2017). Up to moderate salinity, plants can extract water to a permanent wilting point

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determined by the combined total of soil matric and osmotic tensions (Sheldon et al., 2017).

Ben-Gal et al. (2009) investigated the use of osmotic tension and electrical conductivity measurements in a salinity tolerance investigation for bean (*Phaseolus vulgaris* L.), corn (*Zea mays* L.), and melon (*Cucumis melo* L.). This work not only identified the impact on yield arising from increasing osmotic tension but also pointed out that as salts can come from mixed ion sources; consideration of osmotic tension based on the number of ions (rather than electrical conductivity) in salt tolerance and salinity crop-response functions would be beneficial for normalizing data sets and be more appropriate in practical applications. Ben-Gal et al. (2009) employed the Van't Hoff equation to investigate the use osmotic potential (tension) in their salinity response studies, concluding that employing osmotic potential measurements could be beneficial in differentiating between osmotic and toxic effects of salinity. Salman et al. (2023) investigated the impact of osmotic potential on evapotranspiration from grass planted in small-scale laboratory lysimeters and employed the electrical conductivity to osmotic tension conversion from the US Salinity Laboratory (US Salinity Laboratory Staff, 1954). Their experimental work pointed out that water tension (matric potential) and the osmotic tension are the main components of the soil water tension and highlighted the strong relationship between osmotic tension and actual evapotranspiration (ET_a). This relationship being of particular importance in water balance studies and irrigation scheduling, in arid and semi-arid regions (Salman et al., 2023).

Currently, there is not a commercially available product that delivers readings of water tension and osmotic tension in a single integrated device. This is surprising given that there are commercially available products that can measure soil moisture and bulk soil electrical conductivity, for example, the Teros-12 (METER Group, http://www.metergroup.com), HydraProbe (Stevens Water, stevenswater.com), and the WET-2 and WET150 sensors (Delta-T Devices Ltd., delta-t.co.uk). In addition to this, there are commercially available dielectric tensiometers that measure the moisture content of a porous matrix component that is in capillary and adsorptive force equilibrium with the surrounding soil or substrate, for example, the Teros-21 and the Teros-22 (METER Group) and the EQ3 (Delta-T Devices Ltd.). Menne et al. (2022) and Goodchild et al. (2016) provide examples of the construction and characterization of a dielectric tensiometer suitable for use in agricultural irrigation applications. Goodchild et al. (2018) presented a novel dielectric tensiometer with a precision irrigation controller for use with soil-free substrates. As a result of these blocks of technology, the ability to measure the dielectric properties of a soil (or substrate) to provide moisture content and bulk electrical conductivity measurements should be transferrable to determining the same properties of a porous matrix component, as employed in a dielectric tensiometer. In this case, laboratory characterization of the porous matrix component to derive the water tension response (that has resulted in the commercial products listed above) would need to be extended to include equivalent bulk electrical conductivity measurements. In the first instance, bulk electrical conductivity characterization could be based on gravimetric measurements taken during evaporative drying, and used to estimate pore water electrical conductivity, in porous matrix components initially saturated with water of known salinity. With such a characterization, it should then be possible to select and apply an existing soil conductivity model. Suitable models to estimate the pore water electrical conductivity within the porous matrix component include Hilhorst (1998), Ewing and Hunt (2006), Rhoades et al. (1976), Mualem and Friedman (1991), and Muñoz-Carpena et al. (2005), from which osmotic tension can be estimated. The key benefit of this type of integrated water tension and osmotic tension sensor is that in situ measurements are performed on water that has been extracted from the soil and is in approximate chemical and hydraulic equilibrium with the soil solution. Furthermore, such an approach removes the requirements for soil-specific calibration, as is the case with soil moisture sensors.

Core Ideas

- An integrated water tension and osmotic tension sensor does not exist.
- A dielectric tensiometer performs electrical measurements on extracted water from the soil.
- Characterization of the porous matrix avoids soil-specific calibrations for osmotic tension.

An integrated water tension and osmotic tension sensor employing dielectric measurement techniques of a characterized porous matrix component offers several benefits, as follows:

1. Dielectric measurements are made on a porous matrix component that includes the saline water extracted from the surrounding soil, which is in approximate chemical and hydraulic equilibrium with the soil solution.
2. The resulting bulk electrical conductivity measurement of a ceramic-based porous matrix component should not be influenced by soil-related electrical conductivity components such as soil particle electrical conductivity (Rhoades et al., 1976) or root electrical conductivity (Rao et al., 2019).
3. Existing soil electrical conductivity models can be applied to derive the pore water electrical conductivity from porous matrix water content and electrical conductivity measurements. Once the electrical conductivity

measurement has been characterized and calibrated for the porous matrix component, there will be no need for soil-specific calibrations.

It should be noted that a standard water-filled tensiometer does not measure (and is not sensitive to) osmotic potentials. Therefore, an important component of the total tension is not measured by a traditional tensiometer.

2 | MATERIALS AND METHODS

The aim of this technical note is to provide a conceptual framework on the general numerical measurement processing stages and key practical next steps to help assess the feasibility of an integrated water tension and osmotic tension sensor, employing technology and methods that already exist commercially or within soil science. In addition to soil science research, such a sensor could be employed in closed-loop irrigation systems in agriculture and horticulture to provide further insights for the integration of real-time fertigation control and the avoidance of yield reducing abiotic stress events. This Technical Note focuses on dielectric tensiometer technology where electrodes are embedded in a porous matrix component to measure the dielectric permittivity, relating to the moisture content of the porous matrix component—and with an appropriate laboratory-based characterization, and once the porous matrix component is in capillary and adsorptive force equilibrium with the surrounding soil, enables the soil water tension to be estimated. An example of this measurement process has been modeled, supported with experimental data and presented as a flowchart (fig. 9 in Goodchild et al., 2016). The generic key stages in this flowchart are summarized as follows: (i) determine the water retention curve for the porous matrix component using a gravimetric method for a range of applied tensions; (ii) determine the resulting the dielectric permittivity response for the porous matrix element as a function of applied tension; (iii) determine the electrode's electrical (dielectric permittivity or capacitance) response; (iv) apply the electrode's electrical response to the sensor's electronics; and (v) derive the sensor response as a function of applied tension for validation against a water-filled tensiometer. By initially modeling the measurement process (Goodchild et al., 2016), sensor performance can be assessed and design changes evaluated. In this case, the model was used to support a significant design improvement, relating to the interface between the electrodes and the porous matrix component, which was then successfully implemented and verified. This work also considered the use of printed circuit board and metal pin–based electrodes with a porous matrix component. The development of such models should enable other electrode and porous matrix component design parameters, such as physical dimensions and electrode arrangements to be evaluated before progressing to the sensor prototyping stage. In addition, further research should include an evaluation of the diffusion behavior of ions from the soil water into the porous matrix component and within the porous matrix component. The results from this activity may impact on the physical design of the porous matrix component and electrode arrangement with regard to the response time to achieve approximate chemical (and hydraulic equilibrium) with the soil solution. Whilst a detailed description of diffusion behavior is beyond the scope of this Technical Note, a useful starting point for this activity is the recent modeling work of Yang et al. (2024), which considers solute diffusion in unsaturated porous media for the porosity range of 0.37–0.6. This research also includes references to recent modeling and experimental results that could be considered in a sensor development program.

However, this Technical Note does not provide details of commercially available sensor designs or technology-specific laboratory methods or the use of electrode and electronic circuit modeling tools that result in sensors that can provide measurements of soil moisture, soil permittivity, and soil electrical conductivity via dielectric measurement of porous media.

An important design requirement for a dielectric tensiometer sensor is to ensure that the electric field is contained within the porous matrix component and is not influenced by the water and salinity conditions of the surrounding soil or substrate. An example of a perforated stainless-steel cage, which achieves suitable electric field containment within the porous matrix component while allowing hydraulic connectivity to the surrounding substrate, is presented by Goodchild et al. (2018).

A further key sensor design requirement is to understand the hydraulic status of the porous matrix component as a function of moisture content. Yiotis et al. (2006) studied the characteristic periods in the drying of a porous material and highlighted the reduction in drying rate as the hydraulic connectivity within the structure breakdowns at a critical moisture content (θ_c) referred to as the percolation threshold. This breakdown in hydraulic connectivity will also result in electrical disconnects within the porous matrix component, which should be observable from dielectric electrical conductivity measurements to provide a value for θ_c that should verify the value obtained from timed gravimetric measurements.

The application of the soil conductivity models, as listed in the introduction, typically requires empirical soil-specific fitting parameters, and in some cases, soil-specific properties such as bulk density, percolation threshold, or soil particle conductivity are derived. To reapply these models for use with a dielectric tensiometer's porous matrix component will therefore require these parameters to be determined as part of the laboratory characterization process. One of the models, the Hilhorst model, appears to be an attractive solution,

as only one "soil-specific" parameter is required to estimate pore water conductivity from bulk permittivity and electrical conductivity measurements. However, Goodchild (2023) illustrated that in the presence of a non-zero percolation threshold, the Hilhorst model can result in an underestimated pore water conductivity value. Therefore, for the remainder of this Technical Note, the Ewing and Hunt model will be considered, as this model is based on percolation theory and accommodates the percolation threshold as a model parameter. The hydraulic performance of the porous matrix component will need to be assessed in the laboratory (as outlined by Yiotis et al.) to determine if percolation breakdown is an issue, and if so, the percolation threshold determined. Should percolation breakdown not be an issue for a particular porous matrix component, it should be possible to evaluate and select alternative electrical conductivity models or the use of piecewise approaches.

The recent work by Sadeghi and Darzi (2023) presented a soil-water retention model that incorporated pore water osmotic potential with the van Genuchten soil water retention model for several high clay content soils. The experimental data employed to develop this new model covered pore water salinities from 0 to 4.28 M NaCl. Osmotic potential, or tension, was derived from the Van't Hoff equation, as shown below.

$$\varphi_p = iRTC \tag{1}$$

where i = number of ion types dissolved in a solution ($i = 2$ for NaCl), R = universal gas constant, 8.314 (L kPa)/(mol K), T = temperature in Kelvin, C = molarity of the solution, mol/L and φ_p has units of kPa.

The molarity, C, is related to the pore water electrical conductivity (Corwen & Yemoto, 2020) as follows:

$$C \approx 10 \times \sigma_{\text{water}} \tag{2}$$

for $0.1 < \sigma_{\text{water}} < 0.5$ dS m^{-1} (Corwen & Yemoto, 2020), where C = molarity of the solution in mmol/L. In the moderate salinity range considered in this work, C is typically <0.1 M.

Equations (1) and (2) are employed in the numerical measurement processing stages described below.

There are a number of options at each stage, which may be determined by the outputs from the sensor's electronics, the properties and performance of the porous matrix component, and available information relating to the chemical composition of the soil water. An overview is presented below.

In a generic form, the numerical processing stages for estimating osmotic tension consists of:

1. obtaining, via the sensor's electronics, values for:
   a. the water content or permittivity,
   b. the bulk electrical conductivity of the porous matrix component,
2. using the above measurements with the preferred (soil conductivity) model to estimate the pore water electrical conductivity of the water in the porous matrix component,
3. converting the estimated pore water electrical conductivity value to osmotic tension.

Figure 1 outlines the process of employing the measured water content and the electrical conductivity of the porous matrix component to estimate osmotic tension. The percolation theory-based Ewing and Hunt model has been considered a suitable approach to estimate pore water electrical conductivity (Goodchild, 2023), from which the US Salinity Laboratory (Corwen & Yemoto, 2020; Salman et al., 2023; US Salinity Laboratory Staff, 1954) approximation ($\varphi_p = -0.036\ \sigma_{\text{water}}$, φ_p has units of MPa) or the Van't Hoff model (Ben-Gal et al., 2009; Sadeghi & Darzi, 2023) can be applied to estimate osmotic tension, as shown in Equations (1) and (2). The selection of the US Salinity Laboratory approximation or Van't Hoff model can depend on the application and the availability of details of the ionic composition of the soil pore water. For general purpose use, the US Salinity Laboratory approximation is suitable and can be equated with the Van't Hoff model, where $i = 1.453$ at 25°C. However, the Van't Hoff model has also been the starting point in ionic specific salt tolerance studies as employed by Ben-Gal et al. (2009) and more recently by Pachepsky et al. (2024).

Whilst commercially available soil moisture and electrical conductivity sensors can output permittivity, soil moisture, and bulk electrical conductivity, the relationship between permittivity and soil moisture is often shown as (Goodchild, 2023):

$$\sqrt{\varepsilon_r} = a_0 + a_1\theta \tag{3}$$

where a_0 and a_1 are soil-specific calibration parameters and are derived from a gravimetric drying method. This approach can also be applied to the characterization of the porous matrix component and offers further flexibility in the application of the conductivity models listed above.

A model that can accommodate a non-zero percolation threshold is the Ewing and Hunt model, which is based on percolation theory. Equation (8) from Fu et al. (2021), following Ewing and Hunt (2006) with the addition of the soil particle surface electrical conductivity (Rhoades et al., 1976), is given as,

$$\sigma = c_4\ \sigma_{\text{water}} \frac{\left(\theta - \theta_c\right)^{\mu}}{\left(1 - \theta_c\right)^{\mu}} + \sigma_s \tag{4}$$

where c_4 is a unitless empirical constant (Fu et al., 2021), μ is an exponent from continuum percolation theory (Ewing & Hunt, 2006) and for a 3D system it has a value of 2, σ_{water} is the pore water electrical conductivity, σ is the bulk soil electrical conductivity, and σ_s is the soil particle surface electrical

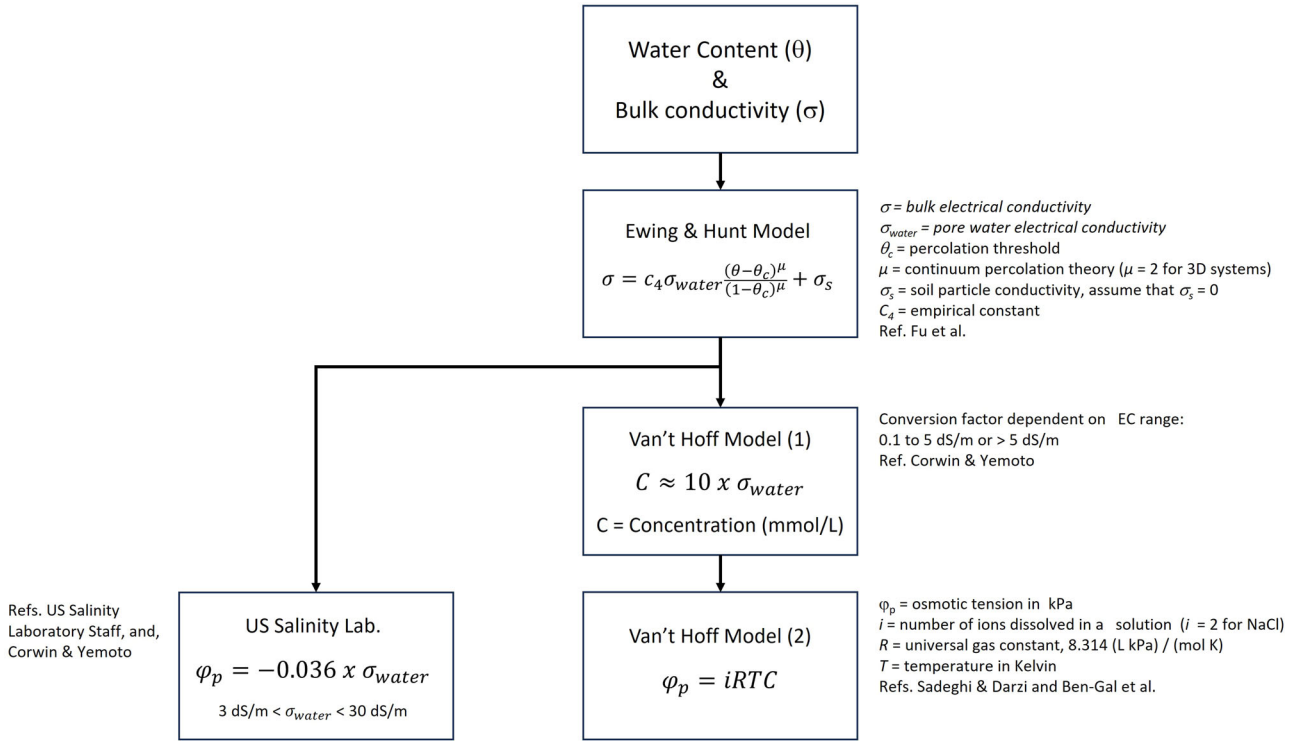

FIGURE 1 An outline of the measurement processing based on sensor electronics that provides water content and bulk electrical conductivity measurements. The Ewing and Hunt model has been considered as a suitable approach to estimate pore water electrical conductivity should a non-zero percolation threshold exist with the porous matrix component (Goodchild, 2023), from which the US Salinity Lab. approximation or the Van't Hoff model can be applied to estimate osmotic tension.

conductivity (Rhoades et al., 1976), which is assumed to have a value of 0 in ceramic-based porous matrix components.

Percolation theory, as presented by Hunt and Ewing (2009), states that μ should adhere to universal values of 1.3 for 2D systems and 2.0 for 3D systems; however, Hunt and Ewing also suggest that deviation from these universal values may well be due to experimental arrangement contributions. These contributions may include electrode contact resistance (Hunt & Ewing, 2009), and so consideration should be given to the electrode to porous matrix component interface (Goodchild et al., 2016).

3 | DISCUSSION

The aim of this section is to present an example of the impact of water tension and osmotic tension as a function of soil moisture for a specific soil type. The general approach outlined in this Technical Note can be easily applied to other soil types and pore water salinities.

In Figure 2, the impact of an evaporative drying soil on pore water electrical conductivity is presented (red line) against soil moisture, starting with a soil moisture of 0.4 $m^3\ m^{-3}$ and a pore water electrical conductivity of 1 dS m^{-1}. The pore water electrical conductivity response is converted into an osmotic tension response (green line) using Equations (1) (with $i = 2$) and (2).

The water tension curve (blue line) is generated using the van Genuchten model (van Genutchen, 1980) for water retention in soil and is given as:

$$\theta = \left(\theta_s - \theta_r\right)\left[1 + (\alpha h)^n\right]^{-m} + \theta_r \quad (5)$$

where θ is water content at water tension h, θ_s and θ_r are saturated and residual water contents of the soil, respectively, α, n, and m are empirical coefficients, with $m = 1 - 1/n$. The soil water retention curve shown in Figure 2 (blue line) employs $\alpha = 2.79\ m^{-1}$, $n = 1.49$, $\theta_s = 0.52\ m^3\ m^{-3}$, and $\theta_r = 0.08\ m^3\ m^{-3}$ for a Silty Clay Loam soil, Gupta et al. (2022). Regarding the impact of salinity on the soil water retention curve, Sadeghi and Darzi (2023) presented a soil-water retention model that incorporated pore water osmotic potential at salinity levels up to 4.28 M NaCl. At these higher salinity levels, significant differences in the water retention curve were observed, mainly relating to the air entry point. For the assessment of osmotic tension in moderate salinity conditions where salinity is <0.1 M, it is assumed that the impact of salinity on the soil-water retention curve is minimal. However, there could be a soil-type dependency that warrants further research, which is beyond the scope of this work.

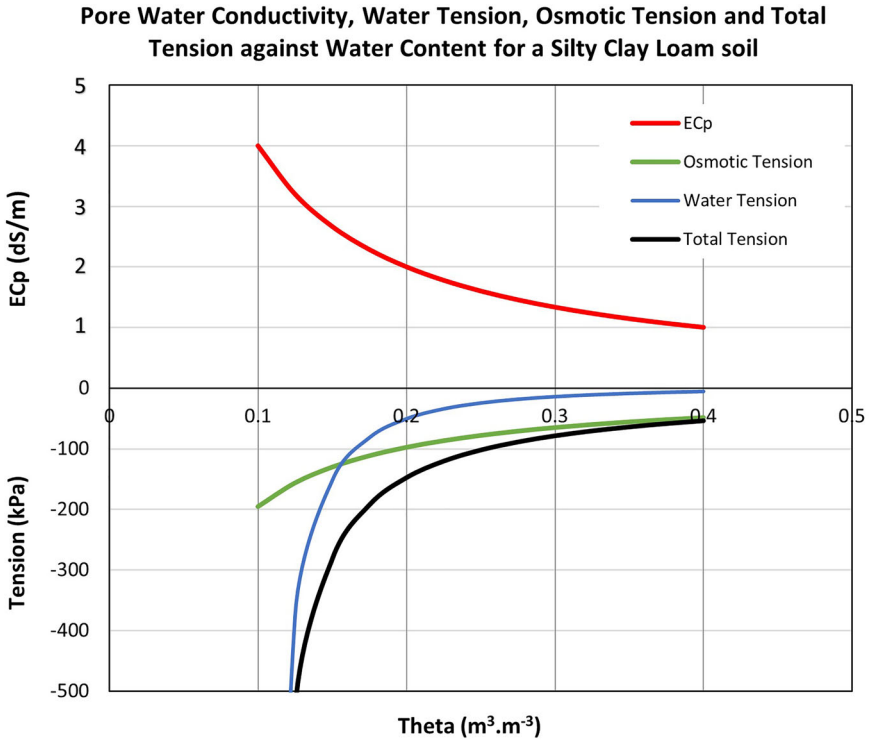

FIGURE 2 An indication of the impact of pore water electrical conductivity (EC_p) on osmotic tension in addition to water tension in a drying Silty Clay Loam soil. The total tension, shown in black, illustrates the significantly increased tension with respect to the water tension value obtained from a standard tensiometer.

The "Total Tension" (black line) shown in Figure 2 is the sum of the osmotic and water tension responses and presents a measure of plant-available water. This soil-based example illustrates that starting with a relatively modest pore water electrical conductivity at a soil moisture level of 0.4 m^3 m^{-3} (where $h = -4.98$ kPa) can result in a significant and increasing osmotic tension under evaporative drying, in addition to the water tension, and is an important component of the total tension that is not measured by a traditional tensiometer.

Figure 2 also illustrates that the dominant tension component of the total tension may depend on the moisture level as well as the salinity level and soil retention curve for a specific soil or substrate. In this illustration, at higher soil moisture levels, osmotic tension dominates, while at lower soil moisture levels, water tension dominates, which is in line with the experimental findings of Sheldon et al. (2017).

4 | CONCLUSIONS

The development of an integrated water and osmotic tension sensor has the potential to be beneficial to the research community studying the impact of water and salinity related stress on plants as well as to commercial growers aiming to improve water and fertilizer resource efficiency and crop yields. Dielectric measurement instrumentation already exists in commercially available soil moisture sensors, which should be transferable to measuring the same properties in the porous matrix materials employed in commercially available dielectric tensiometers.

In the literature, the mathematical models to derive pore water electrical conductivity from bulk soil properties and the conversion of pore water electrical conductivity to osmotic tension already exist. The choice of pore water electrical conductivity model will be dependent on the drying performance of the porous matrix component and is critical to the accuracy of the osmotic tension measurement. The successful development of a prototype integrated water tension and osmotic tension sensor will initially require further research into (1) characterizing the drying performance of the porous matrix component, (2) assessing the efficacy to contain the electric field within the porous matrix component to be able to make reliable electrical conductivity measurements, and (3) an evaluation of the diffusion behavior of ions from the soil water into the porous matrix component and within the porous matrix component.

The methods outlined in the Technical Note can be easily applied to other soil types when the van Genuchten model parameters are known (e.g., Gupta et al., 2022) to predict the impact of water and osmotic tensions. At this time, in situ real-time studies of this type require separate sensors to determine water tension and pore water electrical conductivity.

AUTHOR CONTRIBUTIONS

Martin Goodchild: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

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