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ARTICLE

Precision and accuracy of time-domain reflectometry and capacitive probes to determine soil electrical conductivity in cranberry production — Technical note[1]

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Abstract: A recent study suggests a sensitivity of cranberry to saline stress. Consequently, monitoring of soil electrical conductivity may help growers to identify areas where plants could be under stress due to salt deposits. We used two different types of probes, a time-domain reflectometry (TDR; model CS645 probe) and a capacitive approach (model GS3 probe) to estimate electrical conductivity (EC) or conductance (*G*). The estimates were compared with measurements of EC in soil pore water using suction lysimeters in a sandy soil exposed to two different irrigation methods and a wide range of salt concentrations in a greenhouse. Linear regression analysis of TDR conductance versus measured EC in pore water gave coefficients of determination (R^2) between 0.24 and 0.98 and required specific calibration to accurately reproduce the suction lysimeter EC values. The GS3 probes had higher R^2 values, between 0.54 and 0.98, and were generally easier to work, gave a better accuracy, and had a regression slope not significantly different from 1, result better than with the TDR probes. For both probes, data averaging increased the accuracy in estimates of soil solution EC, as did specific calibration of the probes for the EC values value within the range of 0–5 dS m^{-1}.

Key words: electrical conductivity, sandy soils, cranberry, precision farming.

Résumé : Dans une étude récente, on laissait supposer que la canneberge est sensible au sel. Si c'est le cas, la conductivité électrique du sol pourrait aider les producteurs à identifier les endroits où la culture subit un stress à cause des dépôts salins. Les auteurs ont recouru à deux sortes de sonde pour estimer la conductivité électrique (CE) ou la conductance (*G*) : un réflectomètre à dimension temporelle (RDT; modèle CS645) et un détecteur capacitif. Ils ont ensuite comparé leurs estimations à la CE de l'eau dans les pores du sol en utilisant un lysimètre à succion sur un sol sablonneux irrigué de deux façons et exposé à une vaste fourchette de concentrations de sel, en serre. La comparaison de la conductance établie au moyen du RDT avec la CE de l'eau des pores par régression linéaire donne un coefficient de détermination (R^2) de 0,24 à 0,98; en outre, il faut procéder à un étalonnage spécifique pour reproduire la CE obtenue avec le lysimètre à succion. Le coefficient de détermination obtenu avec la sonde GS3 est plus élevé (de 0,54 à 0,98). Cette dernière est généralement plus facile à utiliser, sa précision est plus grande et sa pente de régression est presque égale à 1, si bien que les résultats sont supérieurs à ceux obtenus avec le RDT. Dans les deux cas, le calcul de la moyenne rehausse la précision de la CE estimée pour la solution de sol, à l'instar de l'étalonnage des sondes pour la CE située entre 0 et 5 dS m^{-1}. [Traduit par la Rédaction]

Mots-clés : conductivité électrique, sols sableux, canneberge, agriculture de précision.

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Abbreviations: FDR, frequency-domain reflectometry; **TDR**, time-domain reflectometry.

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Introduction

Worldwide, soil salinity has become a major agricultural issue, limiting the productivity of numerous salt sensitive plants (Bohn et al. 2001). Recent studies suggested that salinity monitoring could be necessary in cranberry production, considering its sensitivity to some salts (Jeranyama and Demoranville 2009; Samson et al. 2016) and the recent use of subirrigation in cranberry fields (Pelletier et al. 2015). Soil salinity can be estimated from measurements of soil pore water electrical conductivity (EC_p) using a bench-top EC meter. This method requires extractions of water from the soil matrix or the use of a soil-saturated paste extract, both of which can be time consuming and labor intensive.

Time-domain reflectometry (TDR) probes can be automated and give highly accurate estimates of porous media water content (θ_w) and bulk electrical conductivity (EC_a). The TDR measures the propagation velocity of a step voltage pulse with a bandwidth of around 20 kHz to 1.5 GHz (Heimovaara 1994). The propagation velocity of an electromagnetic plane wave depends on electromagnetic properties of the soil through which it travels. It follows that the permittivity of a soil can be determined by measuring the time that it takes the wave to traverse the probe. The permittivity of a soil can be related to its water content (Topp et al. 1980), and the attenuation of the reflected signal along the probe gives information about its electrical conductivity (Rhoades and Schilfgaarde 1976). Many authors have studied the relations among θ_w, EC_a, and EC_p. Notably, Rhoades et al. (1989) suggested a theoretical relation among these parameters (eq. 1):

$$EC_a = EC_p T \theta_w + EC_s' \quad (1)$$

where EC_s' is the apparent electrical conductivity of the soil solid phase, and T is a transmission coefficient. For TDR, EC_a is linked to bulk conductance G through a probe constant K_p that is determined using a calibrated KCl solution (Ward et al. 1994):

$$EC_a = GK_p \quad (2)$$

The linearity in eq. 1 is valid for values of EC_p ranging from 2.5 to 56 dS m^{-1}, whereas a curvilinear relationship develops when EC_p is lower than 4 dS m^{-1} and θ_w is constant (Nadler and Frenkel 1980) because a current flow can be created between a solid-solution series-coupled element acting in parallel to solid and liquid pathways (Rhoades et al. 1989). New models that build on the work of Sauer et al. (1955) have proven to be more accurate under both low EC_p and θ_w conditions (Rhoades et al. 1989, 1990). A model proposed by Hilhorst (2000) (eq. 3) was validated for a broad range of soil types with a $\theta_w >$ 10% and an electrical conductivity of pore water up to 3 dS m^{-1}.

$$EC_p = \frac{\varepsilon_p EC_a}{\varepsilon_b - \varepsilon_{EC_a=0}} \quad (3)$$

where ε_p is the real portion of the dielectric permittivity of the soil pore water, ε_b is the real portion of dielectric permittivity of the bulk soil, and $\varepsilon_{EC_a=0}$ is the real portion of the dielectric permittivity of the soil when bulk electrical conductivity is 0. Hilhorst (2000) suggested a value of 4.1 for ε_{EC_a}.

Despite a precise and well-adapted model, multiple factors can affect the accuracy of TDR probes. The use of cables and multiplexers attenuates the applied and reflected signals (Castiglione and Shouse 2003), and as the length of the cable increases, the error in water content also increases, especially in saline soils (Bilskie 1997). A high soil electrical conductivity is also known to affect the accuracy and resolution of TDR water content measurements (Hook et al. 2004). In a sandy matrix, TDR-based water content measurements were overestimated when $EC_p > 8$ dS m^{-1} (Dalton 1992; Sun et al. 2000). Moreover, depending on the geometry of the probes, differences in the measurement volume can also result in inconsistent results due to variable salt distribution over space (Robinson et al. 2003). Finally, geometry will affect the range of bulk EC measurements.

The desire to improve the accuracy and efficiency of these instruments has led to the development of a variety of probes that are designed for specific soil and environmental conditions (Jones et al. 2002). TDR probes are not only known to be very accurate but also relatively expensive and may require tedious calibration for EC_p determination (Ward et al. 1994; Caron et al. 1999). Capacitive soil sensors and frequency-domain reflectometry (FDR) probes, using relative dielectric permittivity of the bulk soil to determine its electrical conductivity and water content (Gaudu et al. 1993), can offer a cheaper alternative to TDR, particularly when multiple probes are needed. The FDR technique creates an electromagnetic field to measure the dielectric permittivity of the surrounding medium. For the specific case of the GS3 probe (Decagon Devices Inc., Pullman, WA, USA) used herein, the sensor's electronics supplies a 70 MHz oscillating wave to the sensor prongs that accumulate electrical charges according to the dielectric of the material, itself proportional to substrate dielectric and volumetric water contents. The internal processor measures charges and calculates the dielectric permittivity from the sensor and later converted to substrate volumetric water content through a calibration equation specific to the media. However, the accuracy of such a capacitive probe needs to be evaluated in comparison with TDR, given mainly the differences in sampling volume, measurement principles, and range of EC measurements. This study was therefore conducted to compare the efficiency of two different probes (TDR probe CS645, Campbell Scientific and GS3, Decagon

Devices Inc.) as a precision farming tool to estimate soil pore electrical conductivity in cranberry production.

Materials and Methods

Experimental setup

Four blocks of undisturbed cranberry plants (*Vaccinium macrocarpon* Ait. 'Stevens') (25 cm L × 25 cm W × 15 cm H) were collected from a 2-yr-old field established on a sandy soil at Saint-Louis-de-Blandford, QC, Canada. Each experimental unit (EU) consisted of a custom-built plastic container (6-mm-thick polycarbonate; 25 cm L × 25 cm W × 42 cm H) with a 0.5 cm hole drilled at the bottom center covered with an open-mesh fabric (SEFAR Nitex 15 μm, Depew, NY, USA). A 3.5 cm layer of glass microspheres (Spheriglass 2900, Potters Industries, Malvern, PA, USA), another mesh fabric, a 20 cm layer of sand from the same field, and a cranberry bed cut block were successively added to build a 38.5 cm high column in each container. Plants and containers were placed in a greenhouse and were irrigated either through overhead or a subirrigation device. Two of the four blocks were equipped with tensiometers (models T-80 and TX-80, Hortau, Lévis, QC, Canada) installed vertically in the center of each EU to a depth of 7.5 cm to monitor irrigation. All EUs under overhead irrigation contained two sprayers (model Spray Stake, Netafim™, Tel-Aviv, Israel), each calibrated to provide 500 mL of rain water per each irrigation event. Subirrigation treatments were obtained by simulating the presence of a water table under the pot, through a connection between the bottom hole of the container and an Erlenmeyer maintaining a constant water height and filled with rain water. Such irrigation devices were used to detect if a different distribution of solutes within the soil profile would be observed for the two different irrigation methods. In addition, different amounts of water corresponding to the local 30-yr average rainfall distribution were applied over the container using a garden watering can. Throughout the experiment, different amounts of salts (K_2SO_4) were added in each EU to obtain EC_p ranging from 0.12 to 15.7 dS m^{-1} (see Samson et al. (2016) for the complete description). Four potassium treatments of 125 (control), 2500, 5000, and 7500 kg K_2O ha^{-1} were surface applied over the duration of the experiment and for the two irrigation treatments, resulting in a 2 irrigation × 4 potassium levels' factorial experiment.

Soil electrical conductivity monitoring

In two of the blocks and in the four treatments, suction lysimeters were installed vertically in the middle of each EU at a depth of 7.5 cm in the soil, corresponding to half the rooting depth and located either 8 cm on the left- or the right-hand side from the container side wall (see explanations below and Fig. 1).

Fig. 1. Position of both CS645 and GS3 probes in the container. The position of the probes was randomly alternated on each side for each EU and the contact between probe head and the container surface sealed with silicon.

Each Thursday, 500 mL of water was applied evenly on top of each EU. A −10 kPa suction force was created within each lysimeter with a suction pump. Ten minutes later, water was collected from lysimeters, and EC_p was measured with a bench-top EC meter (*SymPhony*, VWR Inc., Radnor, PA, USA). The overall operations lasted 2.5 h to collect all samples. Soil solution samples were collected with the suction lysimeter weekly over 10 wk. Meanwhile, within the same blocks, 16 TDR and GS3 probes had initially been installed horizontally 8 cm from the left-hand or right-hand side to the side wall, so that each container was equipped with the two probes and one suction lysimeter (see above). The positions of the probes and lysimeter were selected to cause minimal interference among one another (Fig. 1). The TDR probe (7.5 cm long, 0.7 cm distance between rods, model CS645, Campbell Scientific, Logan, UT, USA) and the capacitive probe (5.5 cm long and 2.3 cm distance between rods, model GS3, Decagon Devices, Inc.) were sealed at their point of insertion (side of the container) with silicon and inserted horizontally (see Fig. 1). Both probes had different sampling volumes: 160 mL for the GS3 probe (Cobos 2015) and 45 mL for the CS645 (based on probe geometry, see Robinson et al. 2003). The measurement range also differed for the two probes, based on manufacturer's specifications, with detection limits of 5 and 25 dS m^{-1} (bulk EC) for the CS645 and GS3 probes, respectively. K_p was assumed to be 6.40 for the CS645, following manufacturer's recommendations. Probe location (left or right) was randomly determined. TDR probes were connected to multiplexers SDMX80

(Campbell Scientific, Logan, UT, USA) and connected to a TDR100 unit and a CR1000 datalogger (Campbell Scientific), which were programmed using equations in Topp et al. (1980). An analysis of the software PCTDR (Campbell Scientific) was performed to select the optimum analysis window, based on the length of the cables (25 m). GS3 probes were connected to a CR1000 (with SDI12 protocol) that was programmed using an equation originally derived in Topp et al. (1980). All data (θ_w, EC_a, and soil temperature) were recorded every 30 min by the datalogger. Each probe variable presented in this article is an average of measurements taken during the 2.5 h period necessary to perform all lysimeter extractions. All EC data are reported after correction for temperature at 25 °C.

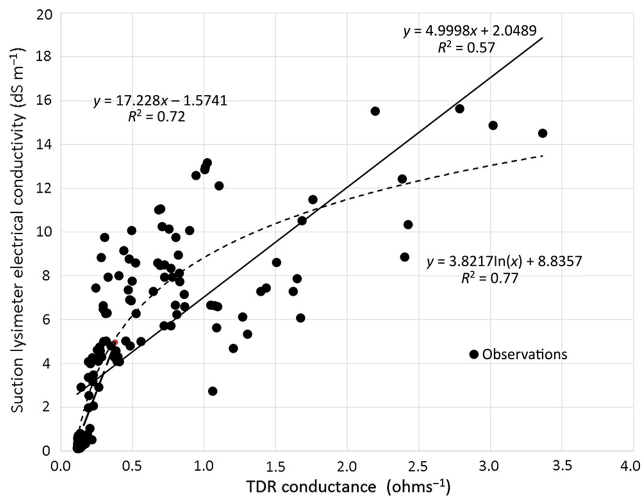
Statistical analysis

A factorial analysis of variance model with blocks was used to compare the effects of irrigation method on solute distribution at different times and for different irrigation treatments. In the absence of a significant effect of irrigation on solute level for a given measurement type, irrigation treatments were considered random, and regression analysis relating bulk electrical conductivity and suction lysimeter data was performed using the GLM procedure in SAS, neglecting irrigation effects. Regressions were also performed using mean values of EC data, for each individual sampling time and potassium treatments, neglecting irrigation treatment.

Results and Discussion

Equations 1 and 2 are used to evaluate that probe provided the best estimate of EC_p measured by the lysimeters. For a measured EC_p range of 0–16 dS m^{-1}, the TDR probes gave an R^2 of 0.57 (linear model) and 0.77 (logarithmic model) (Fig. 2), whereas the GS3 probes gave an R^2 of 0.59 (linear model) (Table 1, Fig. 3). Relationships based on lysimeter EC_p values less than 5 dS m^{-1} increased values of R^2 for the TDR data but not for data collected with the GS3 probes (Table 1). This finding was somewhat expected, given the lower measurement range of the CS645 TDR probe (0–5 dS m^{-1}). Moreover, to achieve such results, TDR data needed to be filtered, omitting values of EC_a that corresponded with unrealistic values of θ_w (e.g., θ_w = 0.80 cm^3 cm^{-3} and higher for sand; data not shown). This phenomenon was probably due to frequent irrigation events pushing down the concentrated solute front, thereby causing higher values of θ_w and EC_p (Dalton 1992; Sun et al. 2000). Finally, a linear regression slope (value of 5.00 and 17.22 for the two salinity ranges) that significantly differed from the manufacturer recommended value of 6.4 indicated that a specific calibration would be needed to improve accuracy, as raised by previous authors in sandy soils (Ward et al. 1994; Caron et al. 1999).

Fig. 2. Pore water electrical conductivity (EC_p) measured in lysimeter extracts as a function of TDR bulk electrical conductance (*G*) obtained using the Rhoades et al. (1989) model (linear: R^2 = 0.57; logarithmic: R^2 = 0.77). Linear regression equation using data corresponding to lysimeter EC_p under 5 dS m^{-1} obtained from the two lowest salinity treatments is displayed in the left upper corner of the figure (R^2 = 0.72).



Using the Hilhorst (2000) equation, estimates of EC_p from TDR-based EC_a measurements did not show good linear relationships with lysimeter EC_p, with R^2 values between 0.24 and 0.36 in the 0–5 and 0–16 dS m^{-1} ranges, respectively (Table 1). This may be due to the high variability in measured values of ε_b and some variability in ε_p with TDR (data not shown). In contrast to TDR, the GS3 probe data did not require postprocessing filtering and also yielded similarly higher values of R^2 for the 0–5 dS m^{-1} and in the 0–16 dS m^{-1} ranges (Fig. 3 and Table 1). The GS3 probes were also easier to work with and responded well to the Hilhorst (2000) model, showing a 0.78 slope with an R^2 of 0.69 (Fig. 3) for the 0–16 dS m^{-1} range, and a slope of 1.05 (not significantly different from 1.00) for the 0–5 dS m^{-1} range (Table 1). However, it is important to note that, despite a slope value that was not different from 1, the *y*-intercept differed significantly from 0 (0.44). Given the fact that cranberry appears as a sensitive species (Samson et al. 2016), and that low EC level detections are usually encountered in field soils, specific calibration is still recommended for application of GS3 probes in cranberry soils.

The lower R^2 value obtained with the TDR may be the result of a much lower sampling volume of TDR CS645 relative to the GS3 probe (45 vs. 160 mL). Hence, a large portion of this variability may be due to the uneven spatial distribution of solutes in the soil, and data averaging could improve both measurement precision and accuracy. Therefore, new regressions were run using averaged values obtained from containers having a same salinity treatment. For TDR data, the regression was

Table 1. Coefficient of determination (R^2) of the linear regression lines of two probe types for electrical conductivity or conductance measurements in a cranberry bed using different salinity models.

		Regression parameters		
Salinity model	Interval (dS m^{-1})	Intercept (s.e.)	Slope (s.e.)	R^2
TDR probes				
Rhoades et al. 1989	0–5	**−1.57** (0.24)	**17.23** (1.20)	0.72
	0–16	**2.05** (0.30)	**5.00** (0.36)	0.57
Hilhorst 2000	0–5	0.03 (0.35)	**0.098** (0.020)	0.24
	0–16	**1.00** (0.47)	**0.149** (0.017)	0.36
Regression on means				
Rhoades et al. 1989	0–5	**−3.01** (0.19)	**25.81** (1.05)	0.98
	0–16	**0.61** (0.35)	**7.54** (0.46)[a]	0.88
GS3 probes				
Rhoades et al. 1989	0–5	**0.85** (0.15)	**5.21** (0.53)	0.54
	0–16	**2.05** (0.28)	**7.11** (0.47)	0.59
Hilhorst 2000	0–5	**0.44** (0.11)	**1.05** (0.08)	0.71
	0–16	**1.05** (0.28)	**0.77** (0.04)	0.69
Regression on means				
Hilhorst 2000	0–5	**0.21** (0.07)	**1.01** (0.03)[b]	0.98
	0–16	0.36 (0.38)	**0.91** (0.06)[c]	0.87

Note: Bold numbers indicate regression parameters (slope and intercept) significantly different from zero.
[a]95% confidence interval of 6.6–8.5.
[b]95% confidence interval of 0.95–1.07.
[c]95% confidence interval of 0.79–1.03.

Fig. 3. Pore water electrical conductivity (EC_p) measured in lysimeter extracts as a function of pore water electrical conductivity estimated by GS3 (dS m^{-1}) data using the Hilhorst (2000) model. Linear regression equation using data corresponding to lysimeter EC_p under 5 dS m^{-1} obtained from the two lowest salinity treatments is displayed in the left upper corner (R^2 = 0.71).

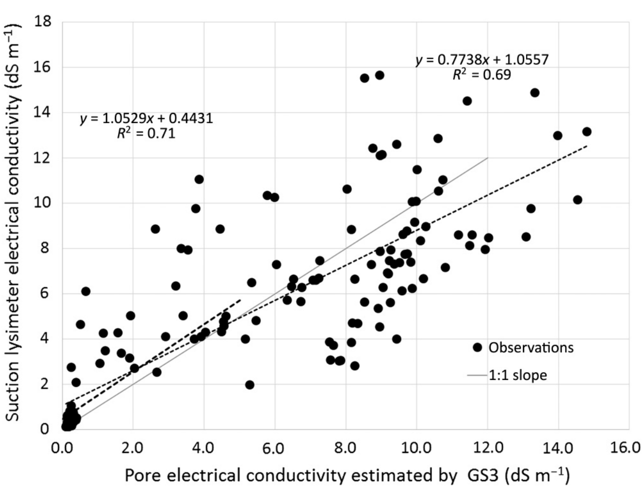
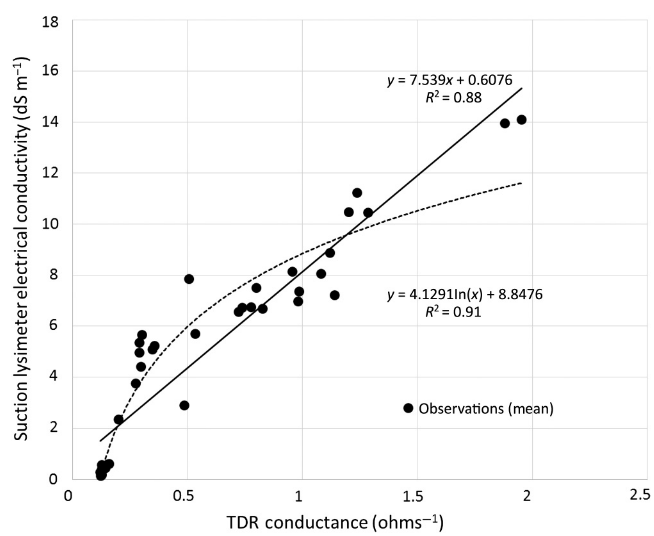
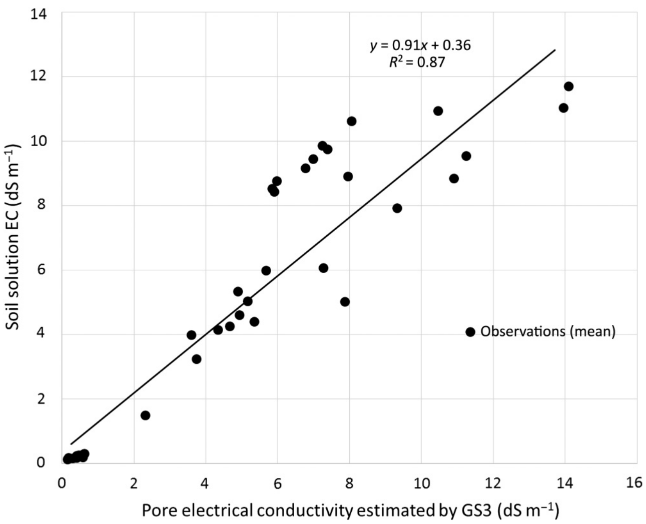


Fig. 4. Pore water electrical conductivity (EC_p) measured in lysimeter extracts as a function of bulk electrical conductance (G) obtained from TDR probes data using the Rhoades et al. (1989) model. Each point corresponds to the mean value obtained for each salinity treatment at a same time.



done using the Rhoades et al. (1989) model (Fig. 4), while the Hilhorst (2000) model was used for GS3 probe data (Fig. 5), as these approaches had given the best results using the raw data for each individual instrument (Table 1). As expected, the R^2 largely improved to about 0.98 for both probes in the 0–5 dS m^{-1} range (Table 1). This clearly suggests that the difference in sampling volume accounted the decreased accuracy in the TDR

Fig. 5. Pore water electrical conductivity (EC_p) measured in lysimeter extracts as a function of pore water electrical conductivity obtained estimated by GS3 (dS m^{-1}) from GS3 probes data using the Hilhorst (2000) model. Each point corresponds to the mean value obtained for each salinity treatment at a same time.



data compared with those collected with the GS3 probe. Also, the slope for the TDR was close to the recommended 6.4 value (confidence interval: 6.6–8.5) with an intercept not significantly different from 0 for the 0–16 dS m^{-1} but was clearly different from 6.4 for the 0–5 dS m^{-1}. Again, it indicated the need for postprocessing calibration to improve the accuracy in the range of low soil EC values that would be characteristic of cranberry soils. One of the very interesting advantages of the GS3 probes was the use of the Hilhorst (2000) equation that gave a direct estimate of EC_p values, most likely to be the one affecting plant growth. Furthermore, the linear regression in Fig. 5 also indicated a slope not significantly different from one for both 0–5 and 0–16 dS m^{-1} regression intervals, an intercept not significantly different from zero for the 0–16 dS m^{-1} range, yet significantly different from zero for the 0–5 dS m^{-1}, despite the fact that no calibration was performed (Table 1).

This implies that the TDR probes using the Rhoades et al. (1989) model would require an independent calibration, probably difficult to achieve for most cranberry growers. For the GS3 probe, the slope was not different from one but the *y*-intercept was significantly different from zero, with a value of 0.21 dS m^{-1} that reflects the accuracy of the EC estimate and still the need for a calibration. However, the difference in slope and intercept, which were much more important for the TDR, indicates that it definitely requires a specific calibration for the TDR probe to be accurate as the difference between true and theoretical value may achieve up to fivefolds, the level in the 0–5 dS m^{-1} range. In a context where an instrument is needed to monitor soil salinity and water content in cranberry production, lower cost and limited need for calibration (at least for the sandy soil investigated here) give a clear advantage of GS3 probes over TDR probes. The GS3 data required very little postprocessing compared with TDR data, and the considerably lower cost of GS3 probes is a definite advantage when multiple probes are needed to increase precision.

These results are probe geometry and soil specific, and analogous studies should be carried out on different soil types, including organic sediments that are commonly encountered in cranberry production. Also, because the performance of the TDR probes was related to differences in sampling volumes, different TDR probes with variable sampling volumes should be analyzed in future studies.

Conclusions

The comparison of two probes indicated that GS3 probes of which design is based on the Hilhorst approach, gave accurate (close to the real value) and (precise = low variability) estimates of soil electrical conductivity, provided multiple samples that are taken, and averaged, in the 0–16 dS m^{-1} with limited need for calibration. Results had a similar precision than TDR estimates using the Rhoades et al. (1989) model but more accuracy. Both probes require calibration for better accuracy in the 0–5 dS m^{-1} range as cranberry fields have typically low EC values.

Disclaimer of Endorsement

The use and reference of the above-mentioned probes and products do not necessarily constitute or imply an endorsement, recommendation, or favoring by Laval University. The views and opinions expressed in this paper do not necessarily state or reflect those of the university and shall not be used for advertising or product endorsement purposes.

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