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Assessment of soil salinity indexes using electrical conductivity sensors

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ABSTRACT

The salinity tolerance of plants can be improved by efficient irrigation management and salt flushing, which require a continuous and precise knowledge of the salinity in the soil or substrate. Soil sensors that measure electrical conductivity play an essential role in monitoring soil salinity. However, the correct interpretation of salinity measurements using soil sensors depends on developing appropriate salinity indexes. This work studied the potential of several salinity indexes based on the bulk EC (ECb) directly measured by soil sensors, and on pore water EC (ECw) estimated by the Hilhorst model (ECwHI). The methodology used in the experiments is based on the simultaneous use of scales and sensors, which allowed the automatic monitoring of the real salinity levels of the substrate, and the conductivity measurements made with the soil sensor. Regression studies were carried out to know how well the proposed salinity indexes explain real salinity. In general, all the indexes were suitable for estimating the relative changes in substrate salinity, as long as they met certain requirements. For example, ECwHI was seen to be a reliable salinity index when substrate moisture was high and constant. However, there was no such requirement when the ECwHI was corrected according to the current substrate water content, or when the salinity index was calculated as the average of the ECwHI values between two successive irrigation events. ECb was an efficient salinity indicator as long as the moisture content was constant, although its accuracy increased at a high moisture level. The findings led us to propose a new salinity index calculated with the slopes of the linear section of the quadratic moisture adjustment, which avoids the need for the substrate moisture content to be constant.

1. Introduction

Water shortages are a very important problem in arid countries, where low-quality, slightly saline waters are frequently used for irrigation purposes. Unfortunately, the current predictions related to climate change indicate that the need to use saline waters for irrigation will only increase. In some areas, such practices are inevitably leading to the salinization of agricultural soil, the main consequence of which will be a reduction in crop yield and quality. In the case of ornamental horticulture, salinity damage produces loss of vigor and alterations in flowering, frequently ending in necrosis and foliar chlorosis, which reduce the aesthetic value of the plant (Bañón et al., 2011). These negative effects of salinity are the consequence of the combined effects of osmotic stress (water stress) and ionic stress (ion toxicity and nutritional deficiency) on the physiological mechanisms of plants (Álvarez et al., 2012).

Among the different ways to approach problems of salinity in ornamental horticulture, one of the most effective is to increase the salinity tolerance of species. Since salinity stress is a common environmental problem and an important factor limiting crop production, the degree of tolerance to salinity of plants in ornamental horticulture needs to be properly assessed (Cassaniti et al., 2009; Villarino and Mattson, 2011; Wu and Dodge, 2005). However, despite the wide range of tolerance to salinity shown by ornamental plants, the salt tolerance of different species has received little attention, and plant selection has mainly been linked to commercial demand. Since ornamental plants constitute a major part of horticultural production, knowledge of a plant's salt tolerance offers great possibilities for water conservation in landscaping (Álvarez et al., 2019). Under these conditions, it is necessary to develop and optimize alternative methods that provide suitable conditions for plant growth under saline irrigation.

One such tool is irrigation management since the salt concentration in the substrate solution increases as substrate moisture decreases. In

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this sense, flushing leaches salts from the root zone, although it implies over-irrigation and a waste of water resources that are subject to environmental and economic limitations (Katerji and Rana, 2014). Since the leaching fraction is a key aspect of irrigation with saline water, knowing how much salt is in the substrate at a given time is of great importance (Sánchez-Blanco et al., 2019). Measuring the salt concentration in the substrate solution is not a rapid task, and so soil or substrate salinity is usually expressed by its electrical conductivity (EC) (Van der Laan et al., 2011). Different ways can be used to measure the EC of a substrate, such as calculating the bulk EC (ECb), the pore water EC (ECw), or the EC of a saturated extract of the substrate or using a dilution test. These EC measurements are related and can be interconverted, but the interpretation of the salinity differs for each measurement/parameter.

ECb has the advantage of monitoring substrate EC in situ. Soil salinity sensors measure this parameter directly, which offers a wide range of possibilities for improving irrigation management with saline water (Incrocci et al., 2009; Incrocci et al., 2010). However, ECb can lead to errors in interpretation of salinity levels, as it includes the combined EC of substrate particles, air, and solution (Corwin and Lesch, 2005; Peter et al., 2011). Since the ECb is very much dependent on soil moisture (Amente et al., 2000; Mualem and Friedman, 1991), its use as a salinity index is limited. This is one of the reasons why the use of salinity indexes based on ECw has become a very common option for saline irrigation management because this measurement represents the salinity that plants "feel". However, measuring ECw does not allow on-site automatic monitoring of substrate EC, as it requires extracting water from the pore water, either by suction compression or displacement of the water before the EC can be measured. It is the need to automatically monitor ECw that has led in recent years to the development of mathematical models that estimate ECw from sensor outputs (Hilhorst, 2000; Kargas and Kerkides, 2012; Lim et al., 2017; Malicki and Walczak, 1999; Wilczek et al., 2012). One of the most commonly used models in this respect was developed by Hilhorst (2000), which estimates ECw using bulk permittivity and EC values, which are directly measured by sensors. However, ECw estimations may be imprecise (Bittelli, 2011). Indeed, several authors have suggested that many factors, such as substrate moisture, temperature, and salinity, can affect the estimation of ECw based on Hilhorst model (Campbell, 2002; Evett et al., 2012; Kargas and Kerkides, 2010; Rosenbaum et al., 2011; Seyfried and Murdock, 2004; Valdés et al., 2015a).

The present study develops salinity indexes based on the measurement of ECb and the estimation of ECw by the Hilhorst model (ECwHI) since both conductivities can be calculated directly or indirectly with the sensor outputs. The proposed indices are based on both isolated and continuous EC measurements and can be calculated under constant or variable humidity conditions. Examples of these indices have been studied by Valdés et al. (2015b), authors who evaluated the effectiveness of the salinity index obtained by ECwHI measurements just after an irrigation event in potted osteospermum plants. Likewise, Valdés et al. (2014a) indicated that the measurement of ECb when substrate moisture is high and constant was an effective tool to mitigate the negative effects of saline irrigation on the production of potted poinsettia plants, while Bañón et al. (2019) found that the average of ECwHI measurements between two successive irrigation events was effective to control salt flushing in potted hydrangea plants.

The main objective of this study was to develop reliable salinity indexes to schedule irrigation and to control salt flushing when EC and moisture soil sensors are used. An irrigation programmer must be able to calculate a salinity index so that the automatic system decides the water volume to be applied just before starting a new irrigation event. Such a decision would be based on a comparison between the saline index value and the predetermined maximum salinity threshold. In order to evaluate the reliability of the proposed indexes, the correlation between the EC values of the above-mentioned indexes and the real substrate EC was studied, taking into consideration different conditions of moisture and salinity.

2. Materials and methods

2.1. Substrate and containers

Black plastic pots (15 cm diameter and 1.5 L volume) filled with mixed substrate were used in this study. The entire lateral surface of the pots was drilled with 5 mm diameter holes to ensure a uniform drying of the substrate. The composition of the mix was (volume) sphagnum peat (60%), coconut fiber (30%), and perlite (10%); each pot was filled with 1440 ml of the mix. The physical parameters that were used to determine the substrate moisture retention curve are: total water holding capacity (62.9%), easily available water (28.5%), water buffering capacity (7.6%), unavailable water (26.8%), and air capacity (38.7%).

2.2. Electronic devices

A GS3 soil moisture sensor (METER Group, Inc. USA) was used in this study. The dimensions of sensor are 9.3 x 2.4 x 6.5 cm, and 5.5 cm needle length. This sensor emits an electromagnetic field to measure the permittivity of the surrounding substrate, which can be converted to volumetric water content (VWC) of the substrate using a calibration equation. The GS3 can measure both temperature and ECb, the former employing a small thermistor, and bulk EC by measuring the resistance between two electrodes to which an alternating electrical current is applied.

Programmable scales (Analytical Sartorius, Model 5201) were used for monitoring the weight of the pots during the experiment period. The scales have a maximum capacity of 5.2 kg and a readability of 0.01 g. One scale per pot and one GS3 sensor per pot was used.

Both scales and GS3 sensors were connected to a CR1000 programmer-datalogger (Campbell Scientist, Ltd, Logan, UT), which was programmed to collect the outputs of the GS3 sensors and the scales every hour using the software Loggernet 3 (Campbell Scientific Inc.). An RS 232 DB-25 cable was used to connect the scales to the datalogger via serial communication.

All experiments were performed in a climate-controlled chamber (MLR-350; Sanyo Electric Co. Ltd.), which was programmed to keep a substrate temperature at about 25 °C throughout the experiment.

2.3. Experimental procedure

Each pot was filled with the substrate. One GS3 sensor was fully inserted into the top of the substrate of each pot with the needles pointing down. Each sensor was placed along the diameter of the pot 4 cm away from the edge. The pots were then placed on scales and the whole ensemble (pot, substrate, sensor, and scale) was then put into the climatic chamber. Three sets were used for each experiment (three repetitions). The standard experiment allowed the substrate to gradually evaporate from its total water holding capacity to a VWC of approximately 10%. The real VWC was calculated gravimetrically and monitored throughout the experimental period by relating the weight measured each hour with the initial weight of the substrate.

A total of seven experiments were conducted to evaluate different electrical conductivities of the substrate pore water (0.5, 1.3, 2.6, 3.9, 5.6, 8.0, and 10.4 dS m^{-1}), which were obtained by using different quantities of sodium chloride to make the solutions. The lowest EC level (0.5 dS m^{-1}) was created by adding deionized water to the substrate. After saturating the substrate of each pot with the corresponding solution, the pots were allowed to drain for thirty minutes. Each pot was saturated and drained repeatedly until the ECw matched reached the EC of the initially added solution (see below: Pour-Through technique).

2.4. Indexes

In addition to the standard readings of the GS3 (permittivity, bulk EC, and temperature), several different indexes of substrate moisture and salinity were calculated, as described below.

2.4.1. *Real volumetric water content (VWCreal)*

The real volumetric water content (VWCreal) of the substrate is the VWC determined by relating at each measuring time the water volume (changing) to the substrate volume (constant) according to Eq. (1):

$$\text{VWCreal} = \text{Vw}/\text{Vs}, \tag{1}$$

where Vw is the current volume of water in the substrate calculated from the difference between current weight of wet substrate (continuous variable) and dry weight of the substrate (153 g), and Vs is the volume of the substrate in the pot (1440 ml). Eq. (1) is multiplied by 100 to express VWCreal as a percentage.

2.4.2. *Volumetric water content estimated by GS3 (VWCgs3)*

Probes such as the GS3 directly measure permittivity, which is used to estimate the VWC of the soil since there is a robust relationship between soil moisture and permittivity (Topp et al., 1980). This is because the main components that affect permittivity in the soil are water, air, and solid particles, and the permittivity of water is much higher than that of air and soil individually. Hence, an analytical relationship (calibration equation) between changes in VWC and the respective changes in permittivity can be established (Topp, 2003).

The manufacturer of the GS3 suggested standard calibration equations for many types of soil and substrate to relate the dielectric properties of a soil or substrate with VWC. However, improved accuracy can be achieved through media-specific calibration (Seyfried and Murdock, 2004). Such specific calibrations are usually performed in the laboratory, where the outputs of the sensor are measured in substrates at progressive moisture levels. In our study, quadratic calibration equations were obtained to estimate the VWC as measured by the GS3 sensor (VWCgs3). The calibrations were made considering each salinity level of the experiment since the permittivity-VWC relationship is altered by salinity (Malicki and Walczak, 1999; Rosenbaum et al., 2011).

2.4.3. *Real pore water electrical conductivity (ECwReal)*

The ECw records were obtained using the Pour-Through technique (Wright, 1986). In brief, 30 minutes after the substrate saturation process, deionized-distilled water was poured over the substrate until 50 mL of leachate was collected in a beaker positioned under the pot. The leachate EC was measured immediately after collection using a conductivity-meter (Dist® 6; Hanna Instruments S.L., Spain). This EC obtained by the Pour-Through method was considered as the real pore water EC value (ECwReal). A separate experiment determined a linear relation between salt concentration and EC by measuring the EC of different concentrations of sodium chloride solutions (2):

$$\text{SaltC} = 0.046 + 0.52\,\text{x}\,\text{EC};\,\text{R2} = 0.999, \tag{2}$$

where SaltC is the NaCl concentration and EC the electrical conductivity of the solution.

Since the y-intercepted value in Eq. (2) is close to zero, its value can be neglected without causing any measurable effect. Accepting this assumption, Eq. (2) results in:

$$\text{SaltC} = 0.52\,\text{x}\,\text{EC}. \tag{3}$$

The substrate salt concentration can also be expressed as:

$$\text{SaltC} = \text{SaltT}/\text{Vw}, \tag{4}$$

where SaltT is the content of total salts in the substrate, and Vw the substrate water volume.

Introducing Vw from Eq. (1) into Eq. (4) gives:

$$\text{SaltC} = \text{SaltT}/(\text{VWCreal}\,x\,\text{Vs}). \tag{5}$$

Combining Eqs. (3) and (5) gives:

$$0.52\,\text{x}\,\text{EC} = \text{SaltT}/(\text{VWCreal x Vs}). \tag{6}$$

By considering Eq. (6) at total substrate water holding capacity (cc) and at a specific time (t), we obtain expressions (7) and (8):

$$0.52\,\text{ECcc} = \text{SaltT}/\text{VWCreal} - \text{cc x Vs}, \tag{7}$$

$$0.52\,\text{ECt} = \text{SaltT} / \text{VWCreal} - \text{t x Vs}. \tag{8}$$

Dividing the equations (7) by Eqn. (8) gives the expression (9):

$$(0.52\text{ECcc})/(0.52\text{ECt}) = (\text{SaltT}/\text{VWCreal}-\text{ccxVs})/(\text{SaltT}/\text{VWCreal}-\text{txVs}). \tag{9}$$

Simplifying both parts of Eqn. (9) results in Eqn. (10), which was used to calculate the real pore water EC at a given time (ECwReal-t):

$$\text{ECwReal} - \text{t} = \text{ECwReal} - \text{cc x}\,(\text{VWCreal} - \text{cc} / \text{VWCreal} - \text{t}), \tag{10}$$

where ECwReal-cc is the pore water EC at total substrate water holding capacity, VWCreal-cc is the real VWC at total substrate water holding capacity, and VWCreal-t the real VWC at a specified time.

2.4.4. *Pore water EC estimated by GS3-Hilhorst (ECwHI)*

As mentioned above, the GS3 outputs can be used to estimate the ECw using different mathematic models. In our work, the ECw was estimated according to the expression of Hilhorst (2000) Eqn. (11):

$$\text{ECwHI} = (\varepsilon\text{w}\,x\,\text{ECb})/(\varepsilon\text{b} - \varepsilon\text{ECb}=0), \tag{11}$$

where ECwHI is the ECw calculated by Hilhorst, ECb is the bulk EC measured directly by the GS3; εb is the real portion of the permittivity of the bulk soil measured by the GS3; εECb=0 is the real portion of the permittivity when bulk EC=0 (offset); and εw is the real portion of the permittivity of the soil pore water, which was calculated from soil temperature using the Eqn. (12):

$$\varepsilon\text{w} = 80.3 - 0.37(\text{Soil temperature} - 20). \tag{12}$$

Hilhorst (2000) recommended a value of 4.1 as a generic offset but also indicated that determining the offset for an individual soil type would improve the accuracy of the calculation. In our experiments, quadratic equations relating permittivity (y-axis) to bulk EC (x-axis) were obtained following the method described above. The y-intercepted value of permittivity was considered as the substrate-specific offset for each level of salinity.

2.4.5. *Moisture-corrected ECwHI (ECwHIw)*

Obtaining the moisture-corrected ECwHI (ECwHIw) consisted of determining the value of ECwHI at total water substrate holding capacity and then computing the conductivity at lower VWC assuming that the salt stays in the soil while the water is being removed (Decagon, 2017). The following equation was obtained (12):

$$\text{ECwHIw} = \text{ECwHIcc x}(\text{VWCreal} - \text{cc} / \text{VWCreal} - \text{t}), \tag{12}$$

where ECwHIcc is the ECwHI at total substrate water holding capacity, VWCreal-cc is the VWCreal at total substrate water holding capacity, and VWCreal-t the VWCreal at a given time.

2.4.6. *Averaged ECwHI between two irrigation events (ECwHIavg)*

This salinity index was calculated as the average of the ECwHI measured every hour between two successive irrigation events (ECwHIavg).

2.4.7. *Bulk electrical conductivity (ECb)*

ECb was measured directly by the GS3 sensor and the measurements at different moisture levels were studied as a salinity index. Also, the value of the slope of the linear part of the regression fit between ECb and substrate VWC after an irrigation event was evaluated as a salinity index.

2.5. Statistical analysis

The statistical relationships between the experimental variables tested were analyzed by multiple regression, using SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA). The significance of the regression slopes was tested through linear regression t-tests at a significance level of 0.001. The coefficients of determination (R^2) were presented as a measure of the representativeness of the regression models.

3. Results and discussion

3.1. The effect of substrate humidity and salinity on ECw

The evolution of ECwReal, ECwHI and ECwHIw values differed as VWC decreased (Figs. 1A, B, and C). The value of ECwReal was higher than those of ECwHI and ECwHIw, regardless of substrate salinity. The ECwReal increased with lower amounts of water, which was to be expected since the salts remain in the substrate while the water evaporates. When the VWCreal fell below 30%, the ECwReal increased dramatically. The higher the salinity, the greater the increase in ECwReal (Figs. 1B and C). Under these conditions (salinity and drought), plants suffer from water stress because the osmotic effect of salts is triggered in a water scarcity scenario, leading to a sharp drop in the soil water potential (Acosta-Motos et al., 2015; Álvarez et al., 2018).

The behavior of ECwHI in relation to the loss of substrate humidity was erratic (Figs. 1A, B, and C). When the VWC of the substrate was high, the difference between ECwHI and ECwReal decreased, especially at low salinity levels (Fig. 1A). However, such differences between ECwHI and ECwReal increased as the salinity level increased (Figs. 1B and C). The decrease in the substrate water content enlarged the differences between these two conductivities since the loss of moisture had little effect on the ECwHI. These results suggest that salinity and drought negatively affect ECwHI (Kargas and Kerkides, 2012; Valdés et al., 2015a). Consequently, ECwHI cannot be considered a suitable index to know how the salinity of the substrate evolves after an irrigation event, because it may produce substantial errors in the estimation, especially when the substrate water content is very low and salinity is high (Figs. 1B and C). Indeed, huge errors occur when the value of the permittivity of the medium (εb) is very small (drought), making the denominator of the Hilhorst equation (ECwHI = [εw x ECb] / [εb - εECb = 0]) very low, which markedly increases the ECwHI value. Negative ECwHI values may also be recorded when the permittivity (εb) value is lower than the corresponding offset value (εECb = 0) (Fig. 1B and C).

In order to minimize errors related to ECwHI, the manufacturer of the GS3 sensor (Decagon Devices, 2017) suggested setting the ECwHI to the maximum water holding capacity of the substrate, and considering the ECw value as a function of the moisture loss in the substrate (ECwHIw). Thus, the ECwHIw at the maximum VWC matches the ECwHI value and the evolution of ECwHIw as the VWC decreases as the ECwReal (Figs. 1A, B and C). This index removes the erratic behavior of the ECwHI, allowing the evolution of salinity after irrigation to be estimated, although it does not prevent the error due to underestimation of the ECwReal induced by salinity (Figs. 1B and C).

3.2. ECwReal-ECwHI and ECwReal-ECwHIw relationships

To throw light on how the ECwHI explains real salinity (ECwReal), the linear regression between both conductivities was studied (Fig. 2A). Since the substrate water content affects the ECwHI measurement (Fig. 1), the statistical study was carried out in five representative substrate VWC levels (60, 50, 40, 30, and 20%). A significant linear relationship between ECwHI and ECwReal was found for all levels of VWC (Fig. 2A). The coefficients of determination (R^2) increased as the substrate VWC increased. As can be observed in Figure 1, differences between ECwHI and ECwReal values were lower as substrate VWC increased. Thus, the value of ECwHI at 60% VWC was approximately half that of the ECwReal value, while the ECwHI at 20% VWC reached values 5-fold lower than the value of ECwHI (Fig. 2A). These results indicate that to determine the substrate salinity more precisely, the ECwHI should be calculated at high and constant VWC, as previously suggested by Scoggins and van Iersel (2006).

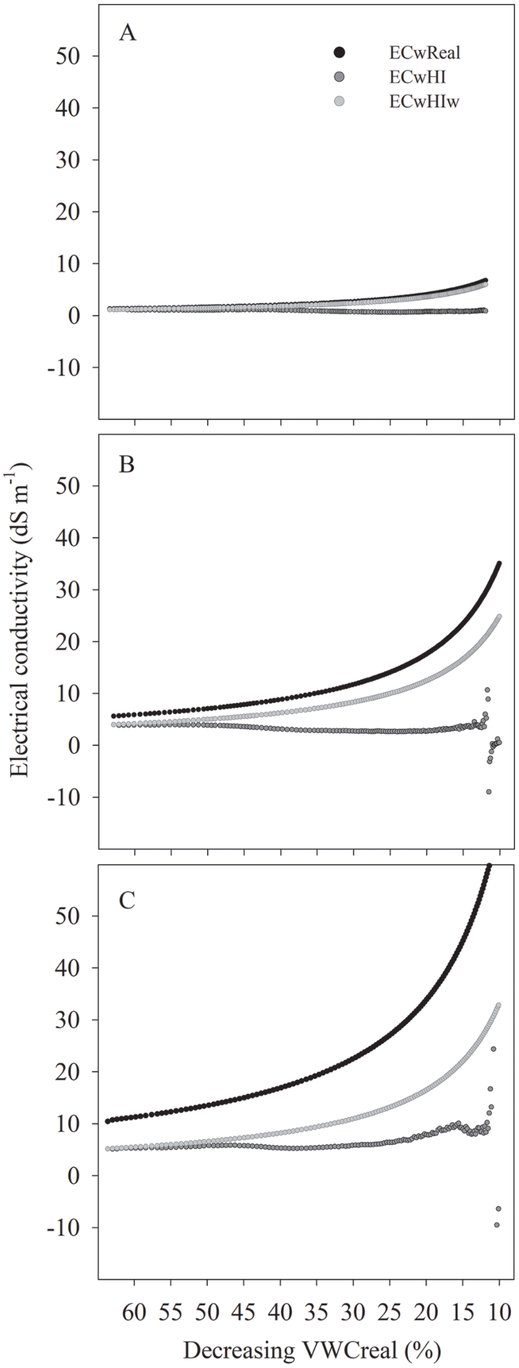

Fig. 1. Evolution of real pore water EC (ECwReal), pore water EC estimated by GS3-Hilhorst (ECwHI) and moisture-corrected ECwHI (ECwHIw) as the substrate dries. Low salinity (1.3 dS m^{-1}, A), medium salinity (5.6 dS m^{-1}, B) and high salinity (10.4 dS m^{-1}, C) levels. VWCreal is the real volumetric water content.

To study the linear relationship between ECwHIw and ECwReal, all the data were analyzed together since both the ECwHIw and ECwReal

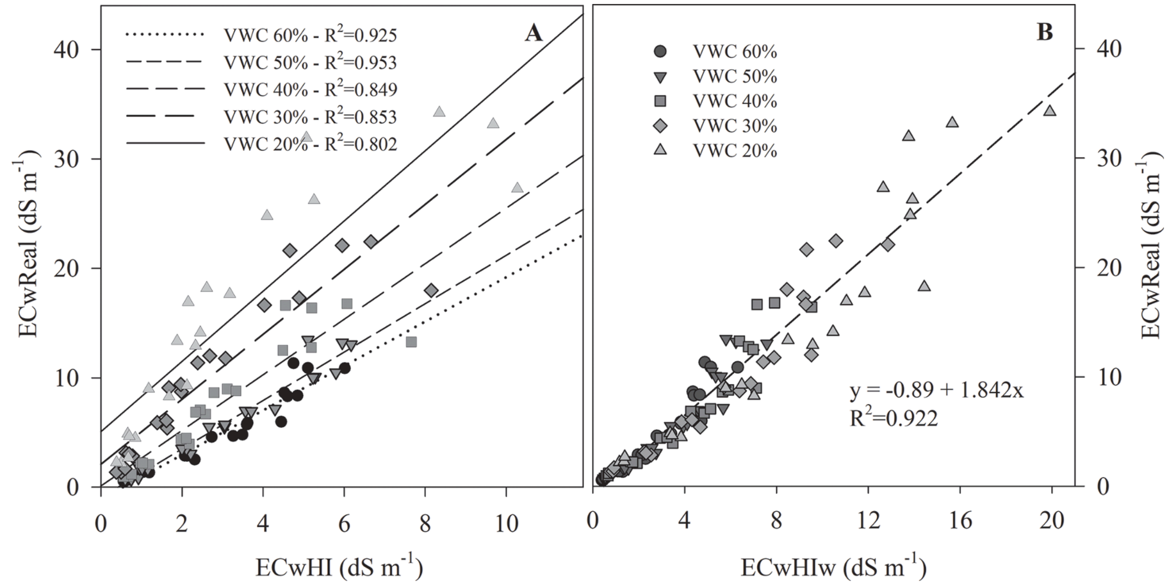

Fig. 2. Linear relationships between real pore water EC (ECwReal) and pore water EC estimated by GS3-Hilhorst (ECwHI) for five volumetric water content (VWC) values of the substrate (20, 30, 40, 50 and 60%) (A), and linear relationship between ECwReal and moisture-corrected ECwHI (ECwHIw) for all VWC levels. All linear adjustments were statistically significant at $P \leq 0.001$.

are a function of substrate moisture (Fig. 2B). A significant linear relationship between ECwHIw and ECwReal was found ($R^2 = 0.992$), which points to the suitability of using the ECwHIw to estimate the salinity of the substrate, regardless of its moisture content.

3.3. The average of ECwHI values between two successive irrigation events

We propose the average value of the ECwHI measurements obtained between two irrigation events (ECwHIavg) as an index of salinity because it considers a large number of ECwHI values that are representative of the different substrate water levels. This index would be more suitable than the indexes based on one or few isolated ECw measurements. The linear fit between ECwHIavg and the ECwReal is presented in Figure 3, which indicates that the index clearly explains the ECwReal. Previous findings suggested that ECwHIavg is a reliable index for managing the flushing of salts from potted hydrangea plants since it avoids an excessive loss of plant quality and minimizing the leaching fraction (Bañón et al., 2019).

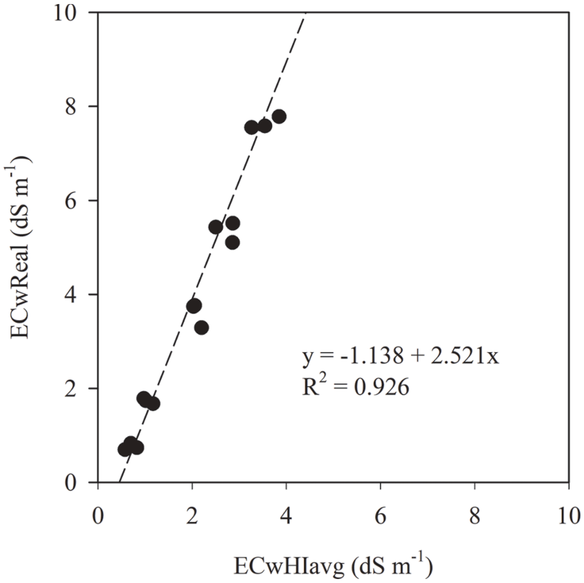

Fig. 3. Linear relationship between ECwHIavg (averaged pore water EC estimated by GS3-Hilhorst between two irrigation events) and ECwReal (real pore water EC). Linear adjustment was statistically significant at $P \leq 0.001$.

3.4. The effect of substrate moisture and salinity on ECb

At any of the salinity levels studied in this work, the moisture content of the substrate had a positive effect on ECb, following a quadratic adjustment (Fig. 4), which indicates that changes in ECb resulted from changes in moisture become more pronounced as the substrate VWC increases. This response of ECb to moisture can lead to a misinterpretation of salinity when ECb is used as a salinity indicator, since a low ECb value may be obtained both at high salinity and low humidity, and low salinity and high humidity levels (Fig. 4). In fact, this is the main reason why ECb is not considered a reliable index for determining substrate salinity (Peter et al., 2011). The effect of moisture on ECb can be

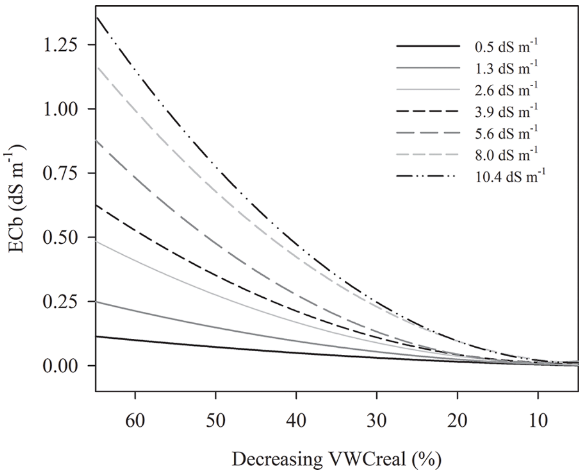

Fig. 4. Evolution of bulk EC (ECb) as the substrate dries for seven levels of salinity (0.5, 1.3, 2.6, 3.9, 5.6, 8.0 and 10.4 dS m^{-1}). VWCreal is the real volumetric water content.

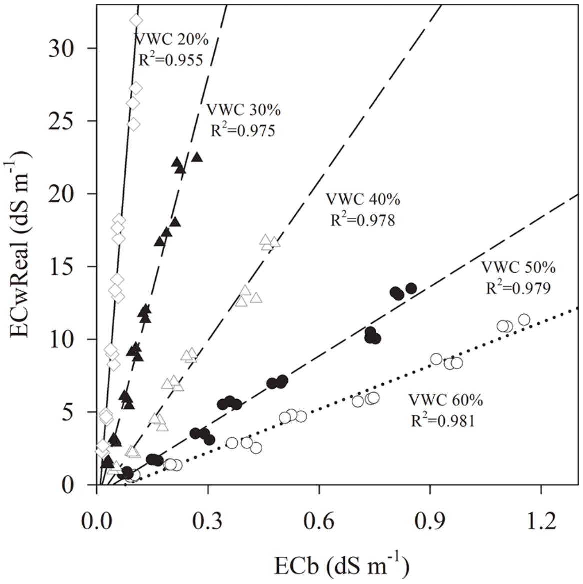

Fig. 5. Linear relationships between real pore water EC (ECwReal) and bulk EC (ECb) for five volumetric water content (VWC) of the substrate (20, 30, 40, 50 and 60%). All linear adjustments were statistically significant at $P \leq 0.001$.

explained by the stronger attraction between free ions and particles in a substrate with little water, which leads to the ions being less mobile in soil, and so the EC falls (Rhoades et al. 1989; Amente et al. 2000). In this sense, Scoggins and van Iersel (2006) indicated that ECb-humidity dependence is due to the fact that water displaces the air in the soil pores, and, since air is a bad conductor of electricity, the more air there is in the substrate (drier substrate) the lower the EC value.

Salinity increased the curvatures of the exponential curves that relate VWCreal with ECb (Fig. 4). Consequently, under constant and high moisture conditions, any change in substrate salinity would lead to ECb values being proportionally higher than those obtained under constant and low moisture conditions. This means that the ECb is more sensitive to changes in salinity when the moisture content is high, and so the determination of salinity will be more accurate. Valdés et al. (2014a) tested the ECb measured half an hour after irrigation, when substrate VWC is at its highest, as a salinity index in potted poinsettia plants, finding that the ECb measured at maximum moisture was an effective index for assessing relative changes in salinity.

3.5. Relationships between ECwReal and ECb

Because of the strong influence of moisture on ECb (Amente et al., 2000; Mualem and Friedman, 1991), the statistical relationships between ECwReal and ECb were determined under constant substrate moisture conditions. Five levels of substrate VWC were studied, and a significant linear relationship between ECb and ECwReal was found at all levels (Fig. 5), as was previously suggested by Rhoades et al. (1989). The degree of correlation between ECb and ECwReal was high, which suggests that changes in salinity are well explained by changes in ECb, over a wide range of substrate moisture levels. Then, since a high substrate moisture level is easier to achieve than an intermediate one, measuring ECb immediately after irrigation and drainage would be convenient. In this respect, Valdés et al. (2015b) found a strong linear relationship between the ECb measured at the maximum water retention capacity of the substrate and the ECw measured by the Pour-Through method in a potted osteospermum crop.

3.6. The slope of the linear portion of the regression line of ECb and VWC after an irrigation event

Although quadratic fits are usually not very intuitive, the ECb-VWC curves presented in Figure 4 suggest that ECb and VWC are closely and linearly related when the VWC is above approximately 35%. For this reason, a regression analysis between ECb and VWCreal was performed, when the substrate VWC was between 35% and 60%, resulted in significant linear relationships at all salinity levels. A study of the slopes of these regression lines indicated significant statistical differences between saline levels (Fig. 6A). Since the slopes become steeper as salinity increases, they could be used to assess the saline status of the substrate.

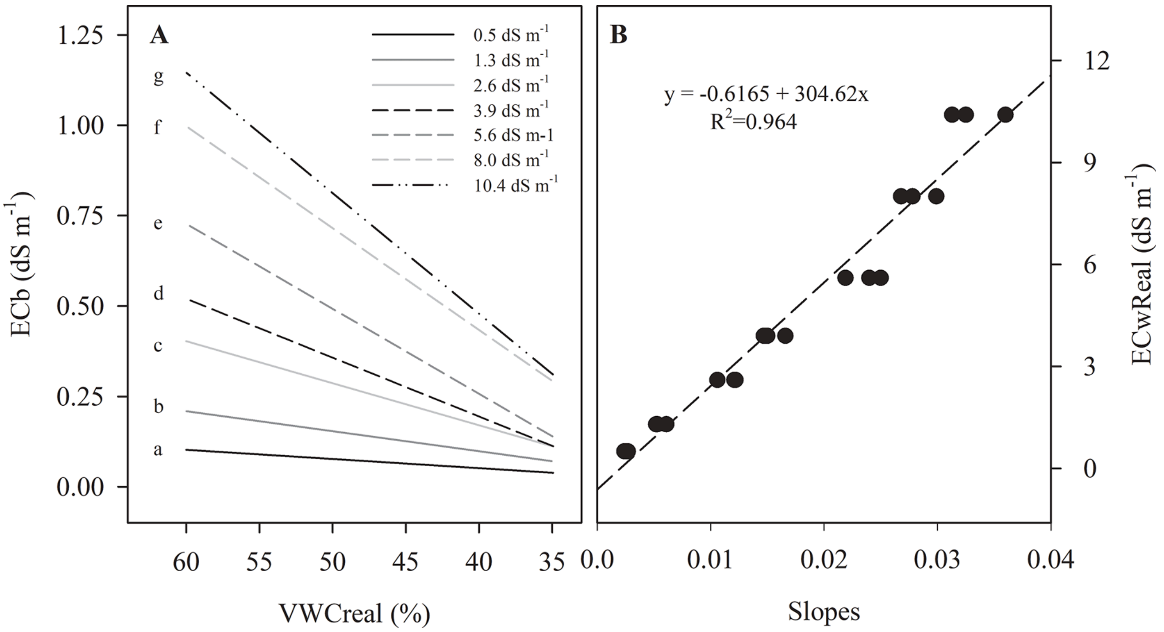

Fig. 6. Linear adjusts between bulk EC (ECb) and real volumetric water content (VWCreal) for substrate VWCreal in the 60-30% range (A). Linear relationship between real pore water electrical conductivity (ECwReal) and slopes of the ECb-VWCreal linear relationship (linear adjustment significant at $P \leq 0.001$) (B). Vertically different letters indicate statistically significant differences between slopes according to linear regression t-tests at a significance level of 0.001.

To confirm this hypothesis, a correlation analysis between the ECwReal and the slope was performed (Fig. 6B), the result of which confirmed the suitability of the slope for use as an indicator of salinity.

However, the limitation of using these slopes is that they need to be calculated in the same moisture range over the whole culture period. We used a substrate with a high-water retention capacity, and the range used to determine the slopes was between 60% and 35% VWC. This coincides with the most common humidity levels obtained with irrigation scheduling in potted plants since the set-point is usually related to the percentage of substrate available water, defined as the difference between the VWC at 1 kPa and 5 kPa (de Boodt and Verdonck, 1972). In our substrate, the easily available water was 28.5% and its depletion could lead to VWC of 34.4 %. Nevertheless, to avoid water stress in the plants it is common to irrigate before the easily available water runs out (Mavrogianopoulos, 2015; Nikolaou et al., 2019). However, the relationship between this water and plant growth is not completely clear since it depends on the characteristics of the substrate and the plant type (Altland et al., 2010). In our experiment, irrigating at 40% VWC would mean a depletion of 80% in easily available water, which is a threshold for maintaining a good plant water status (Enciso et al., 2007). Thresholds below 40% would bring the plants closer to water stress, and levels below 35% would only make sense in drought-resistant plants since the easily available water would soon be depleted.

3.7. *The efficiency of substrate VWC estimation using a GS3 sensor*

A significant and strong linear relationship between VWCreal and VWCgs3 was found, regardless of the salinity level (Fig. 7). Furthermore, the coefficient of determination (R^2) of the VWVreal-VWCgs3 relation was close to one. Both aspects indicate that the GS3 can provide very accurate estimations of the VWCreal of the substrate. The simultaneous use of GS3, scales, and pots automatically enabled monitoring the values of permittivity and substrate weight. As a result, hundreds of points relating VWC and permittivity were obtained, compared with a much lower number of points when standard manual calibration is used (Starr and Paltineanu, 2002). In this way, we were able to obtain very precise specific humidity-permittivity calibration curves.

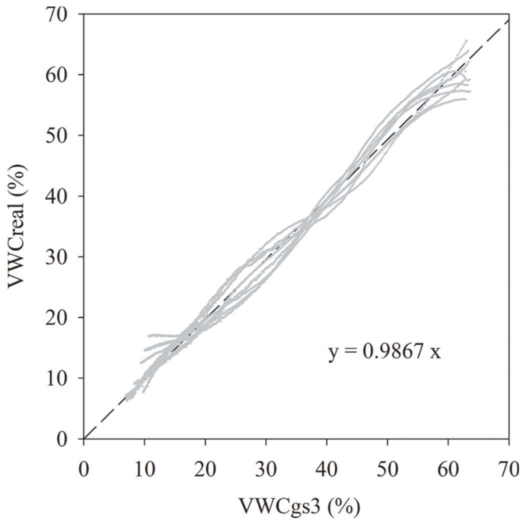

Fig. 7. Relationship between real volumetric water content (VWCreal) and volumetric water content estimated by GS3 (VWCgs3) considering all levels of salinity (moisture calibration equation). Linear adjustment was statistically significant at $P \leq 0.001$.

4. Conclusions

Salinity indexes are an effective tool for assessing the direct relationship between substrate EC and plant growth. For optimal saline irrigation management, we need effective salinity indices as determined directly or indirectly with the soil EC sensors. This work has assessed several salinity indices based on ECb, which is measured directly by the sensor, and on ECw estimated with Hilhorst's mathematical model. The irrigation methodology used in this experiment led to a uniform distribution of the salt in the substrate. However, when potted plants grow under saline conditions and drip irrigation, the salt distribution in the root ball is irregular (Valdés et al., 2014b). This could increase the variability of the measurements made by the sensors and consequently affect the calculation of saline indexes. To minimize this issue, the salinity thresholds for different varieties should be determined under real growing conditions.

The following conclusions can be drawn based on the results of this study:

a) The ECw calculated using the Hilhorst equation (ECwHI) does not adequately reflect the real salinity when the moisture of the substrate is changing. However, this conductivity measurement can be a valid indicator to express relative changes in the saline status of the substrate if measured at high and constant humidity.
b) Determining the ECwHI at the maximum water retention capacity of the substrate and linking its behavior with the decrease in humidity (ECwHIw) allows the salinity to be monitored as the substrate dries, which is more accurate as the salinity level falls.
c) Salinity produces an error of underestimation of the ECwReal when the ECwHI and the ECwHIw are used. A decrease in humidity will increase this error, which is considerable when the ECwHI is measured at very low humidity and high salinity levels.
d) The average ECwHI value between two successive irrigation events (ECwHIavg) is closely related to the real salinity, and its measurement adds reliability compared to individual measurements of ECw.
e) Salinity can be efficiently monitored from *in situ* measurements of ECb when the substrate VWC is the same at the time of measurement. This efficiency increases when ECb is measured at high VWC values.
f) We propose using a salinity index based on the slope of the linear section of the exponential curve that relates the ECb to VWC, which would be tested in future field experiments.
g) The scale-sensor method enables very precise humidity-permittivity calibration curves.
h) More experiments should be carried out to relate the values of the salinity indices with different levels of saline stress, which will permit salinity thresholds to be established for each index in different crops.

Author statement

Sebastián Bañón: Conceptualization, Writing - Review & Editing, Investigation. Sara Álvarez: Methodology, Formal analysis, Validation. Daniel Bañón: Software, Methodology, Formal analysis. María Fernanda Ortuño: Formal analysis, Funding acquisition, Investigation. María Jesús Sánchez-Blanco: Conceptualization, Funding acquisition, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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