Dielectric sensors in an automated facility for testing salt tolerance of irrigated field crops

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Abstract: Current data on salt tolerance of field crops are scattered, partly conflicting, and not well defined. This paper describes a field test facility designed to test the salt tolerance of crops under well drained irrigated conditions. Irrigation is provided to groups of 8 replicas of test fields, at seven different levels of salt concentration expressed in electrical conductivity (EC) ranging from 1.7 dS/m to 35 dS/m.
A unique feature of the system is that each of the 56 test fields is equipped with one or two dielectric sensors to allow quasi continuous monitoring of soil volumetric water content (VWC) and bulk electric conductivity (EC_b). The aim is to provide a preliminary assessment of the added value of the sensors, based on two consecutive years of testing.
Sensor calibration was performed in the laboratory, and different models to relate bulk EC to pore water EC in dependency of the VWC or dielectric permittivity as measured by the sensor were tested and parameterized. Overall, the root mean square error of the tested models with one or two parameters did not differ very much, and was in the range of 0.57-0.59 dS/m in terms of soil bulk EC. However, the models differed in their robustness against inversion to obtain pore water EC from measured bulk EC. A simple one-parameter model was preferred, showing a ratio between bulk EC and pore water EC that is proportional to the VWC as measured by the sensor. The laboratory calibration was then cross validated by comparing sensor EC readings with the EC of pore water extracts obtained from suction cup samples in the field. It appears that the laboratory calibration formula overestimates the pore water EC at low EC (5 dS/m), and underestimates it at high EC (25 dS/m).
The extensive data of 2013 revealed that a simple direct proportionality between pore water EC and sensor bulk EC, without any correction for VWC, can circumvent the difficulties with the calibration. This result must be treated with care as in the current field tests the soil water content was always very high. In addition, such relationship can be used only when actual pore water samples are taken, which is not always

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practical.Overall, there is a good correlation between the time trajectories of the suction cup samples and the sensor time series, while the latter provide much more details about the dynamic behavior. Fairly large differences in bulk EC between different fields within the same irrigation treatment group were observed in both the sensor readings as well as the samples, suggesting that these differences are real. Also, within a field, sensors my differ, but the time trajectories are very similar. In the drained conditions used here the average pore water salinity was largely imposed by the irrigation EC, despite variations in rainfall and evapo-transpiration over the season. Despite the difficulties with the laboratory calibration, the higher temporal detail provided by the sensors offers excellent opportunities for advanced control of soil salinity to support crop salinity tolerance tests.

Keywords: salt tolerance, electrical conductivity, volumetric water content, soil sensor, calibration, salinity

1. Introduction

Agricultural food production in semi-saline environments may be seen as an opportunity to partly counteract the loss of suitable arable land due to climate change and other reasons. In this context, it is important to be able to assess the tolerance of various crops to salinity under well irrigated conditions. Salt tolerance of crops has been extensively studied, mainly in the frame of drought and salinization due to irrigation. Shannon and Grieve (1999) provide a review in an attempt to unify the widely scattered information. From this review it becomes clear that any realistic salt tolerance experiment must be based on well-defined methods and principles. Also, it becomes clear that the overall tolerance of some crops to salinity may be dependent on the salinity experienced during certain growth stages.

These considerations motivated the establishment of the field test facility described in this paper. The novelty in this facility is the additional use of a large array of soil sensors for quasi-continuous monitoring of bulk EC, volumetric water content and soil temperature. The idea is that the feed-back provided by the sensors might ultimately be used to provide controlled salinity conditions, with the option to make them variable throughout the season.

The overall objective of the test facility is to determine crop salt tolerance curves under realistic outdoor irrigated conditions. The first two years have been used to gain experience, and to obtain crop tolerance curves under practically constant EC values in the field over prolonged periods of time. The specific objectives of the current paper are to judge the suitability of continuous EC and VWC sensor readings for testing the success of the irrigation and drainage regime. The core of the paper is devoted to assessing the performance of sensors against less frequent salinity information obtained from soil samples and pore water extractions. Also, the sensors provide information about within-field and between-field variation that is relevant for crop salt tolerance testing.

2. Description and operation of the test facility

2.1 Fields, equipment and soil

The field test facility is located at Texel Island, The Netherlands, where fresh water and sea water is available for mixing in any desired ratio (see Figure 1). The desired composition was realized by controlled mixing using a proportional-integral-derivative (PID) controller with frequency regulated pumps from both sources, which allowed time-based automatic pulse irrigation during the day of a number of drained test fields with eight randomly chosen spatial replicas of 8x20 m^2. Seven different treatments with increasing irrigation EC, targeted at 0, 4, 8, 12, 16, 20 and 32 dS/m, were established. Because of the natural EC of the fresh water source, the real EC of the "0" treatment was 1.7 dS/m. During switching from one regime to the other, surplus water is discharged, until a steady EC is reached, after which the irrigation valve is opened.

In 2012 the amount of irrigation was 13.7 mm/d, distributed over four daily pulse events, in 2013 11.4 mm/d distributed over two events per day. The high irrigation intensity keeps the soil moisture content permanently close to the field saturation point and maintains a continuous downward percolation of water so that the salt concentration in the root zone is quite constant over time and not much different from the EC of the irrigation water.

Each of the 56 fields was equipped with one or two Decagon GS3 dielectric permittivity / EC sensors to yield long-term time trajectory records of volumetric water content (VWC) and pore water salinity (EC_p). The sensors were connected to a field bus, divided into two groups, and readings were stored sequentially in a MySQL database with a sampling interval of about 5 minutes. The fields were drained by pipes at 60 cm depth and 5 m spacing. Such an intensive drainage system keeps the water table well below the root zone even under intensive irrigation and on days with high rainfall.

The soil is sandy with an organic fraction of 2%. The soil particle density is about 2.5 Mgm^{-3} and the bulk soil density at saturation is about 1.5 Mgm^{-3}. The soil was homogenized for the entire facility in the year before the operation started. Despite homogenization, there are known differences between various corners of the test site regarding porosity (between 0.39 and 0.42), and water holding capacity (between 0.24 and 0.27 $kg[water]kg^{-1}[dry\ soil]$).

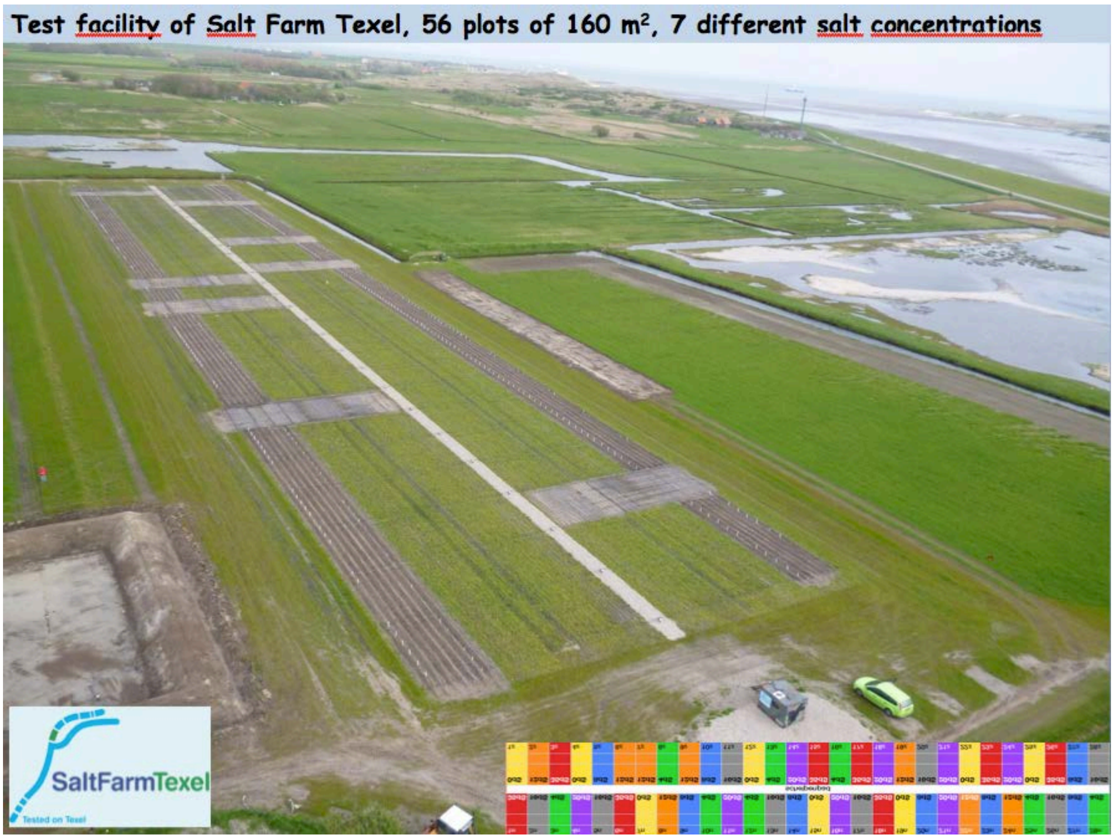


Figure 1
Aerial view of the test location. The fields are on both sides of the light diagonal strip that contains the irrigation main pipe. The pump equipment and computer facilities are in the small container, just visible at the lower right. The colors in the insert give an impression how the 7 treatments are distributed 8-fold over the 56 fields.

2.2 Sampling and sensor data processing methods

On 7 days during the growing season in 2012 and 11 days in 2013, in the morning, suction samples of the pore water were taken with a rhizon soil water sampler, at three different depths, for 3 (2012) and 4 (2013) fields per treatment. In the analysis presented in this paper the 'suction cup' EC was averaged over depth, and is further denoted as EC_p. In addition to these pore water extracts, also soil samples were taken to relate the pore water EC_p to the commonly used extract of 1:2 diluted soil samples $EC_{1:2}$, or the EC of the saturated paste extract (EC_e). In general, there is a good correlation between EC_p, $EC_{1:2}$ and EC_e.
The Decagon GS3 sensors were placed by digging a pit and then pushing the pins of the sensors in horizontal direction into the side wall, while orienting the housing in a diagonal direction, so that after refilling the sensors were covering a depth of 15 to 20 cm. The sensors measure bulk EC, denoted by EC_b, , i.e. the EC of the mix of soil, pore water and air, which is much lower than the EC of the extracted pore water. Thus, it is necessary to provide a calibration, which was performed by laboratory measurements, as described below. Next, the calibration is tested by pairing suction cup pore water sample EC's and sensor EC's. For this purpose sensor EC's were

obtained by taking the average of the sensor readings between 10 and 12 h on the sampling days.

3 Sensor calibration

3.1 Volumetric Water Content (VWC)

The sensors measure bulk dielectric permittivity (ε_b), bulk EC (EC_b or σ_b) and temperature (T). By factory default, the Topp equation (Topp *et al.*, 1980) is used to derive Volumetric Water Content (VWC, θ) from the dielectric permittivity. However, at high salinities, it is known that this is less accurate. Therefore, lab tests were done by gradually wetting dry soil with water with a pre-defined EC, similar to the salinity levels that were used under field conditions (from 1.7 up to 35 dS/m). The sensor VWC (θ_s) shows good linearity with the true VWC, at least up to 20 dS/m, but the slope increases with increasing salinity. Thus, a correction to the sensor VWC was made as shown in Eq. (1)

$$\begin{gathered}\hat{\theta} = (1 - p\sigma_b)\theta_s \\ p = 0.064\end{gathered} \tag{1}$$

where $\hat{\theta}$ denotes the calibrated VWC, and θ_s is given by

$$\begin{gathered}\theta_s = a\varepsilon_b^3 + b\varepsilon_b^2 + c\varepsilon_b + d \\ a = 5.89 \cdot 10^{-6}; b = -7.62 \cdot 10^{-4}; c = 3.67 \cdot 10^{-2}; d = -7.53 \cdot 10^{-2}\end{gathered} \tag{2}$$

The parameter p was estimated by minimizing the sum of squared differences between model prediction and lab observations. The quality of the fit is shown in Figure 2.

It is observed that points belonging to the highest EC treatment (37.9 dS/m) show the most scatter. It was established that the validity range of Eqn.(1) is up to irrigation EC's of 25 dS/m (corresponding to about 4 dS/m bulk EC, see below).

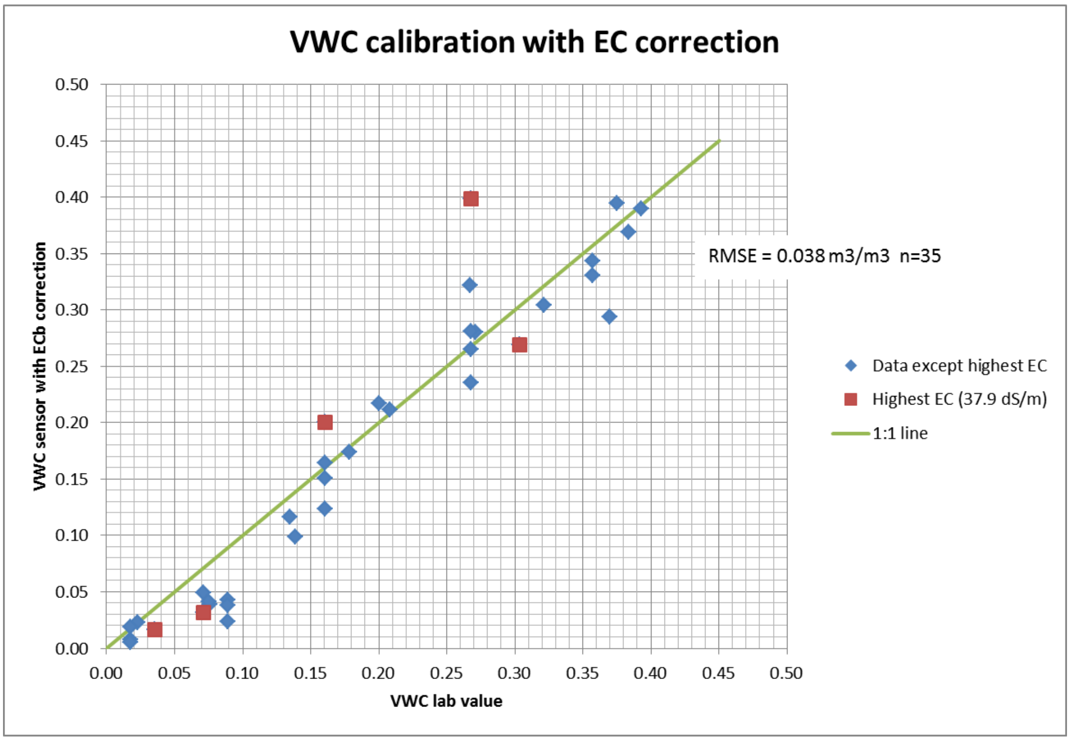


Figure 2
EC correction on sensor VWC (lab data 2012) according to Eqn. (1).

3.2 Electric Conductivity (EC), theory

The bulk EC (EC_b or σ_b) as measured by the sensor is not only determined by the EC of the pore water (EC_p or σ_p), but also by the soil matrix and the air in the pores. In addition, there can be ionic interaction between the surface of the soil particles and the pore water, that also influences the ECb. As bulk EC and bulk dielectric permittivity are determined by the same soil characteristics, there is a link between these two. Brovelli and Cassiani (2011) provide an extensive theoretical model to relate bulk EC to pore water EC at various degrees of water saturation, and they also unify models cited in the literature. In sandy, saline soils with water contents of more than 20% of saturation, which corresponds with the conditions in the test facility (VWC>0.08 m^3[water]m^{-3}[soil]), their model boils down to Archie's second law (Archie, 1942), which can be stated as

$$\hat{\sigma}_b = p_1 \theta^{p_2} \sigma_p \tag{3}$$

Following Mortl *et al.* (2011) other models tested were the one that under certain assumptions can be derived from the more elaborate model presented by Rhoades *et al.* (1990)

$$\hat{\sigma}_b = (p_2 \theta^2 + p_1 \theta) \sigma_p \tag{4}$$

and one and two-parameter variants of the empirical model of Vogeler *et al.* (1996)

$$\hat{\sigma}_b = (a\theta + b)\sigma_p + c\theta + d \quad (5)$$

i.e.

V1: $$\hat{\sigma}_b = p_1\theta\sigma_p \quad (6)$$

V2: $$\hat{\sigma}_b = (p_1\theta + p_2)\sigma_p \quad (7)$$

V3: $$\hat{\sigma}_b = p_1\theta\, \sigma_p + p_2\theta \quad (8)$$

The four-parameter variant resulted in slightly better fits, but the parameters b and d are very small, and a chi square test with Akaike's information criterion revealed that the introduction of more parameters was not justified.

While in these relationships the true volumetric water content (θ) must be used, this is unpractical as the true VWC can only be known by taking samples. We found from the laboratory tests that equally good parameterizations can be obtained by taking the VWC as obtained directly from the sensor (θ_s). It is possible that this is due to the fact that the sensor VWC is based on the directly measured permittivity, which, in turn, is related to the soil pore structure and soil material. However, attempts to use the bulk permittivity directly failed. In particular, the (inverse) equation of Hilhorst (2000), Eqn.(9) - found to work well for glass beads -, yielded poor results for the 2012 laboratory data:

$$\hat{\sigma}_b = \frac{(\varepsilon_b - p)}{\varepsilon_w\, f\{T\}} \quad (9)$$

where ε_w is the permittivity of pure water (80.3), and $f\{T\}$ a temperature correction given by

$$f\{T\} = 1 - 0.00461(T_s - 20) \quad (10)$$

and T_s is the soil temperature in ^{o}C, as measured by the sensor. A possible reason might be that in the dielectric permittivity based equations the real part of the complex permittivity must be used, which was not available.

3.3 Electric Conductivity (EC), lab data calibration

The lab data are shown in Figure 3. It is clearly seen that the relation between pore water EC and bulk EC depends on the VWC. This is also reflected in the models.

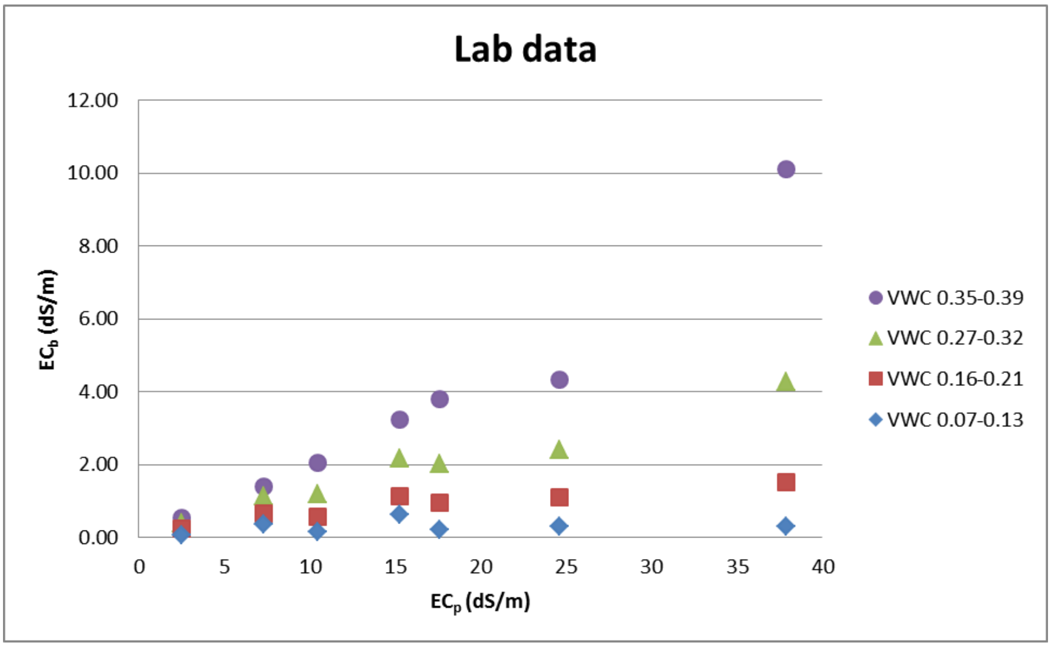


Figure 3

Lab sensor ECb versus imposed pore water ECp. Due to the dilution method, the VWC is varying over the samples, precluding a direct comparison. The VWC ranges are shown as legend in the figure.

Table 1 summarizes the results of the parameter estimation from the laboratory data for the various models.. The column EC_b RMSE represents the root mean square error in ECb units (defined as the square root of the sum of squared differences between model and data divided by the number of degrees of freedom, i.e. the number of points minus the number of parameters). In the laboratory experiments above, the pore water EC was the independent parameter that is known by experimental design, but in any practical application, the pore water conductivity must be derived from the measured sensor conductivity. In addition, pore water EC is of larger agronomical interest as this is the EC seen by the roots. Therefore, the equations above were inverted to yield pore water EC. The root mean square errors of the reconstructed pore water EC's without recalibration are presented in the last column of Table 1. Because pore water EC is much larger than bulk EC, the errors are also considerable larger.

As can be seen in Table 1, the models differ in their robustness against inversion. Model V2, and to a lesser extent Archie's model are less robust than the other models. This is due to the amplification of the uncertainty in parameter p_2. Model V3 has the disadvantage that after inversion negative pore water EC's may result under certain extreme conditions. For all these reasons the inverse of the simple model V1 is the preferred model.

$$\hat{\sigma}_p = \frac{\sigma_b}{p_1 \theta_s} \tag{11}$$

The inverse equation can be re-calibrated against the lab data by interchanging the dependent and in-dependent variable, to provide the lowest possible error. The re-calibrated parameter and RMSE are shown in the table as well.

Table 1 EC Laboratory Calibration Models

Model			EC_b RMSE	EC_p RMSE after model inversion
	p_1	p_2	(dS/m)	(dS/m)
Archie	0.347	1.186	0.576	11.77
Rhoades	0.234	0.131	0.570	7.12
Vogeler (V1)	0.313		0.587	6.25
Vogeler (V2)	0.325	-0.006	0.590	26.69
Vogeler (V3)	0.242	2.056	0.514	7.00
Eqn. (11, inverse V1) (recalibrated)	0.343			5.97

Note1: Valid for VWC>0.08 and $\sigma_b < 4$ dS/m (roughly equivalent to $\sigma_p < 25$ dS/m.
Note 2: equations use sensor VWC θ_s.

3.4 Electric Conductivity (EC) , validation

Next, it was tested how the laboratory calibration worked out when the modelled EC_p (according to Eqn. 11) from all sensors in 2013 were compared to the observed ECp from the suction cup samples. The result is shown in Figure 4.

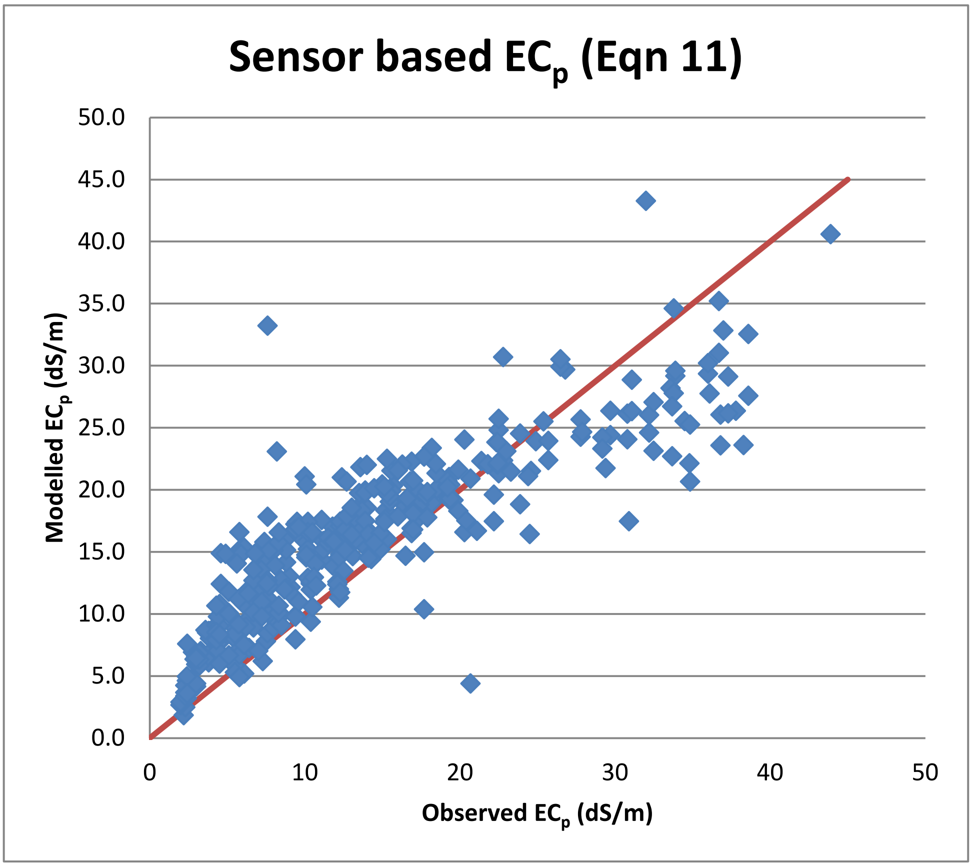


Figure 4

Result of the reconstruction with Eqn. 11 (with $p_1 = 0.343$) of pore water EC from sensor bulk EC and sensor VWC (averaged on the sample days over period 10-12 h) as compared to the suction cup pore water samples.

Clearly, at low EC the modelled EC$_p$ overestimates the observed EC$_p$, and at high EC it underestimates it. Similar results were obtained with model V2. The points at the high end with the most scatter originate from the fields with 35 dS/m irrigation. Obviously, the calibration models are not yet fully adequate to describe the field situation, and more work is needed to analyze this further. It should be kept in mind that both the observed suction cup sample values, as well as the sensor values underlying the reconstruction of the pore water based on the calibration models have uncertainty with them. The suction cup samples are means over three depths, and differences of up to 1 dS/m can easily occur. The sensor values are derived from means over a couple of hours, but it is known that due to irrigation twice a day, there can be differences even within this time period. So, altogether this is a typical example of an errors-in-variables estimation, which may need more elaborate methods. In addition, on retrospect, and in the light of eqn. (11), it might be better to compute σ_b/θ_s at each sensor sample, and take the time average of these. The sensor equation could perhaps be further improved by taking the temperature into account, but the correction according to Eqn. (10) yielded slightly less good results, rather than bringing an improvement.

3.5 Direct comparison of sensor bulk EC and suction cup samples

Rather than relying on the laboratory calibration, the field data can be used in their own right. When sample pore water EC_p values are plotted against sensor EC_b,, omitting the values associated with the very high salinity treatment (EC 35), the result of Figure 5 is obtained. Surprisingly, it appears that ECp can be computed from sensor ECb even without any correction for VWC. That this works is probably due to the fact that the fields are well irrigated, and hence have VWC's in the high range.

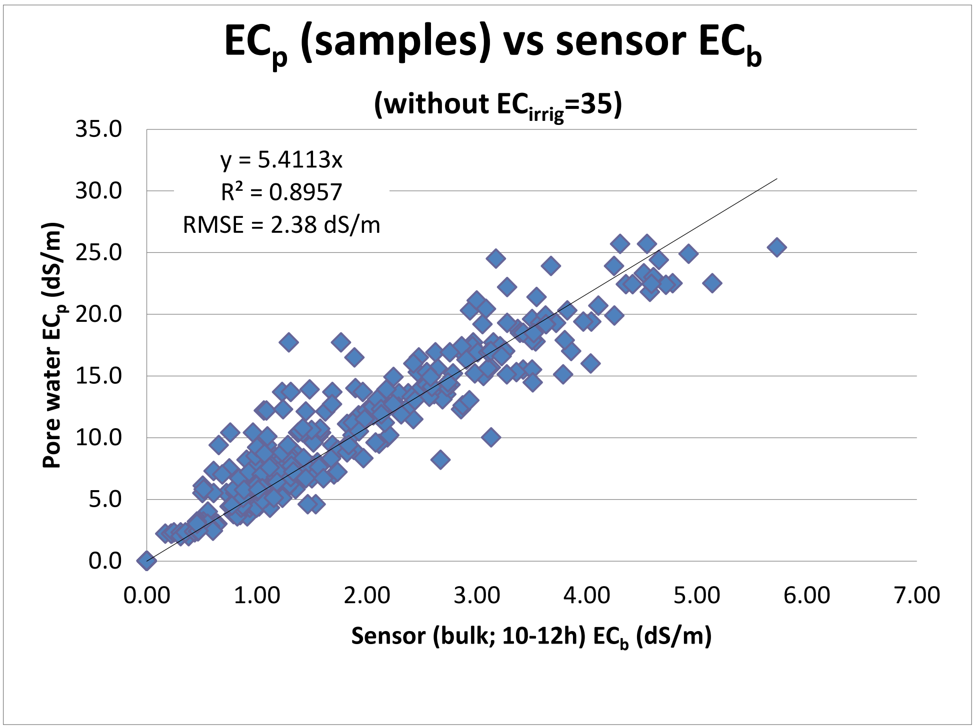


Figure 5

Direct plot of observed suction cup pore water EC versus sensor bulk EC, all 2013 results, omitting the fields irrigated with water of EC = 35 dS/m.

This suggests the linear model, valid for near saturated soils of

$$\hat{\sigma}_p = \frac{\sigma_b}{p} \tag{12}$$

with in our case $p = 0.185$. On average the pore water EC is about 5.4 times higher than the bulk EC as measured with the sensor. Although the fit is much better than with the laboratory calibration, still large errors on individual locations and instances in time are possible. Figure 6 shows an histogram of the EC_p errors, showing that the linear expression is quite adequate, with slight bias of about 1 dS/m.

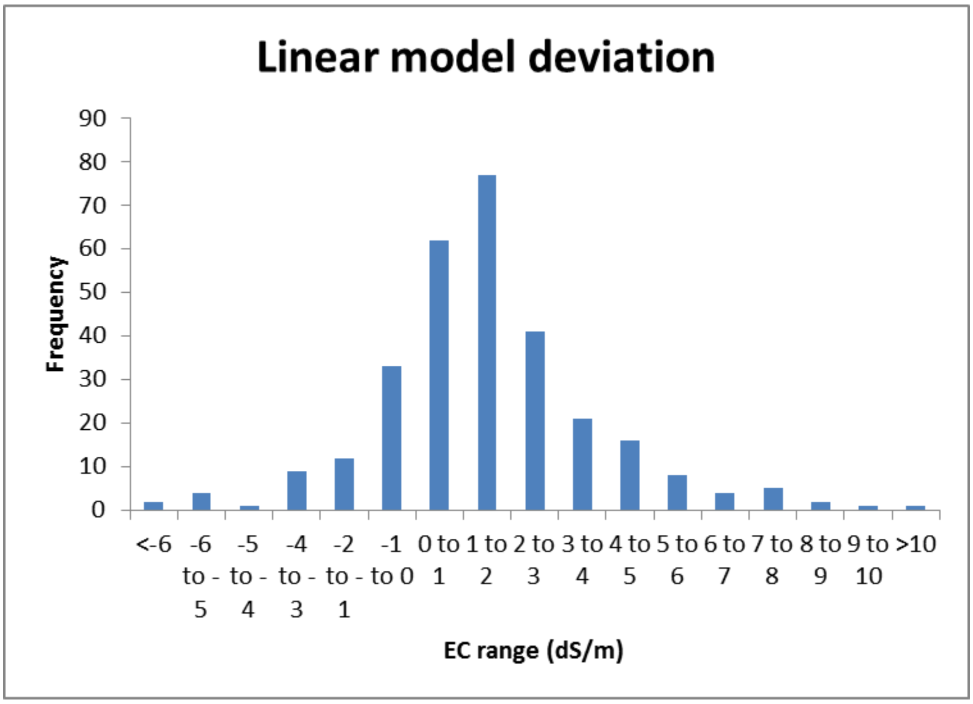


Figure 6
Histogram of the deviations of the linear model.

Although it is tempting to use the simple proportionality, this needs to be reconsidered in future scenarios where the water content may be allowed to drop.

4 Sensor based time trajectories

The sensor behavior can be plotted in many ways. As there are 56 fields and even more sensors, and, in addition, different variables (raw and calibrated EC and VWC, for instance) it is only possible to show a selection of the most striking results of the time trajectories.

4.1 Patterns in response to irrigation and variation between fields

Figure 7 provides an idea of the sensor patterns in response to irrigation over a couple of days. A graphical user interface has been developed to show the data.

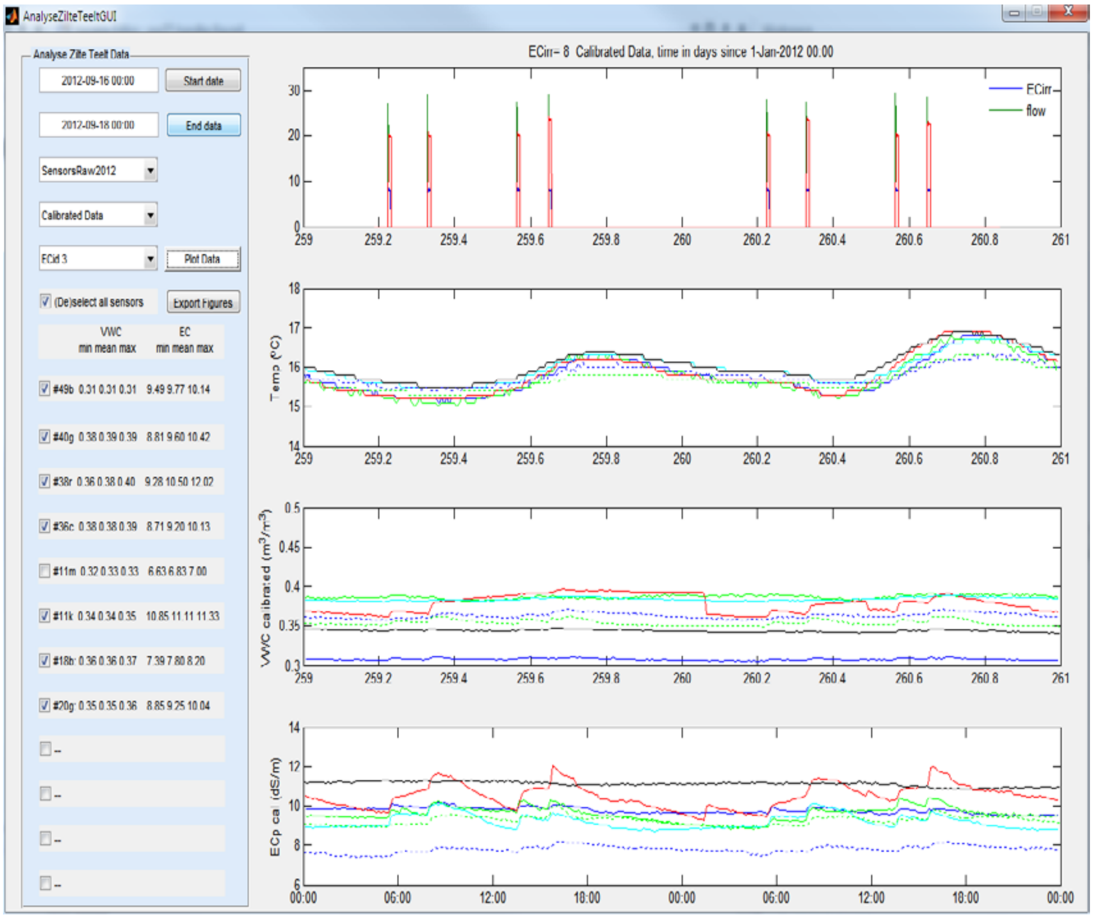
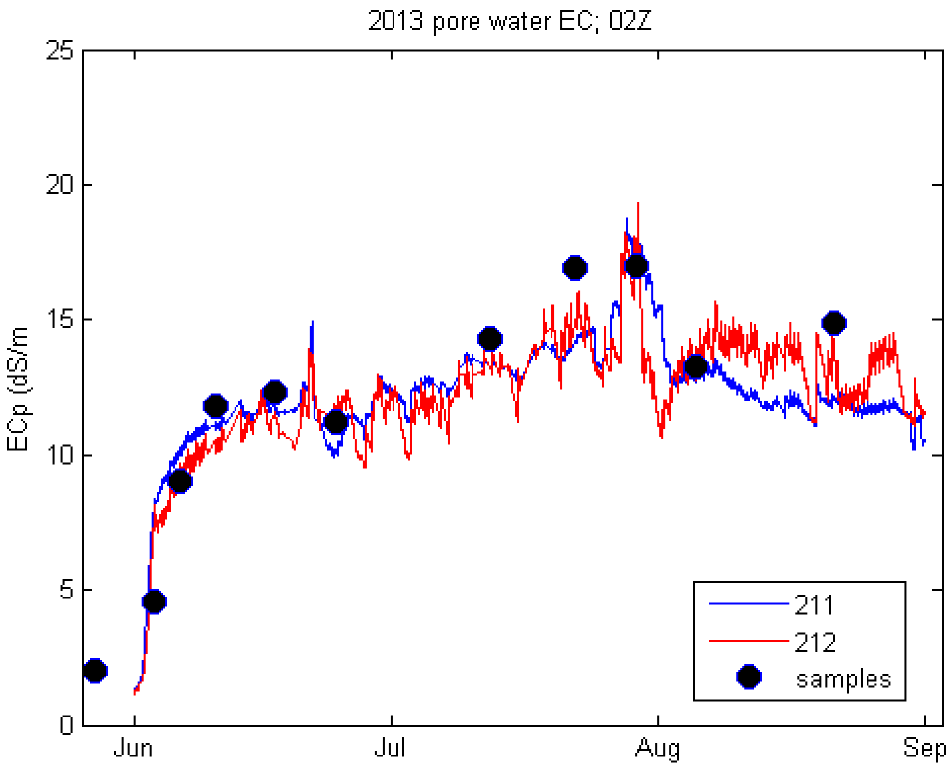


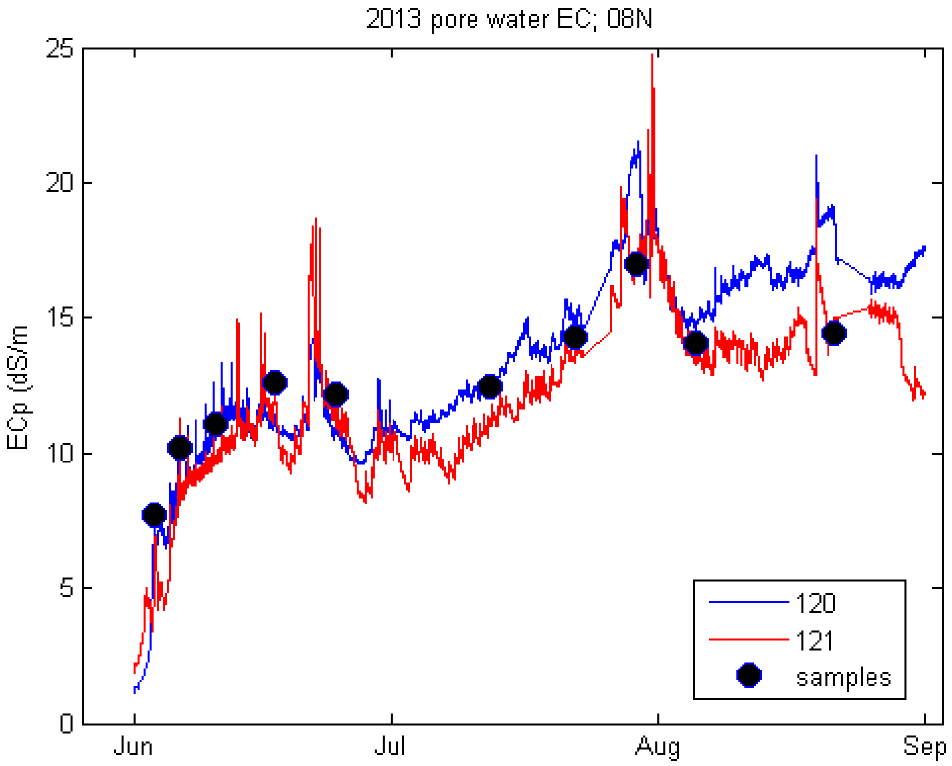
Figure 7
Time trajectories of sensors in 6 fields with irrigation treatment of 8 dS/m for September 16 and 17, 2012. Top panel: irrigation events (flow and concentration), next panels: temperature, VWC and EC_p, respectively.

First of all it is clear that the patterns in fields that are supposed to be replicas may differ, both in level as well as in dynamics. While the VWC for most sensors is between 0.35 and 0.4, in one of the fields the VWC seems considerably lower. Looking at the pore water EC (lower panel), in some fields the immediate response to irrigation is clearly visible, while other fields are less dynamic. It is not fully clear why this is the case, but it is known that in 2012 some sensors had corrosion wear, which was prevented in the 2013 measurements by modifications in the design by the manufacturer. Overall, in 2013, sensors showed more consistency (see below).

4.2 Comparison with suction cup samples and in-field variation

Encouraged by the good correlation between suction cup measurements and sensor data, seasonal plots were made of both for comparable fields in 2013. To exclude that the differences between fields were caused by individual sensor bias, and to test the consistency of sensor readings within a field, in 2013 a number of fields was equipped with two sensors. Figures 8a-c show the seasonal pattern of each of the two sensors, as well as the suction cup samples over time, for three fields with the 12 dS/m irrigation treatment.





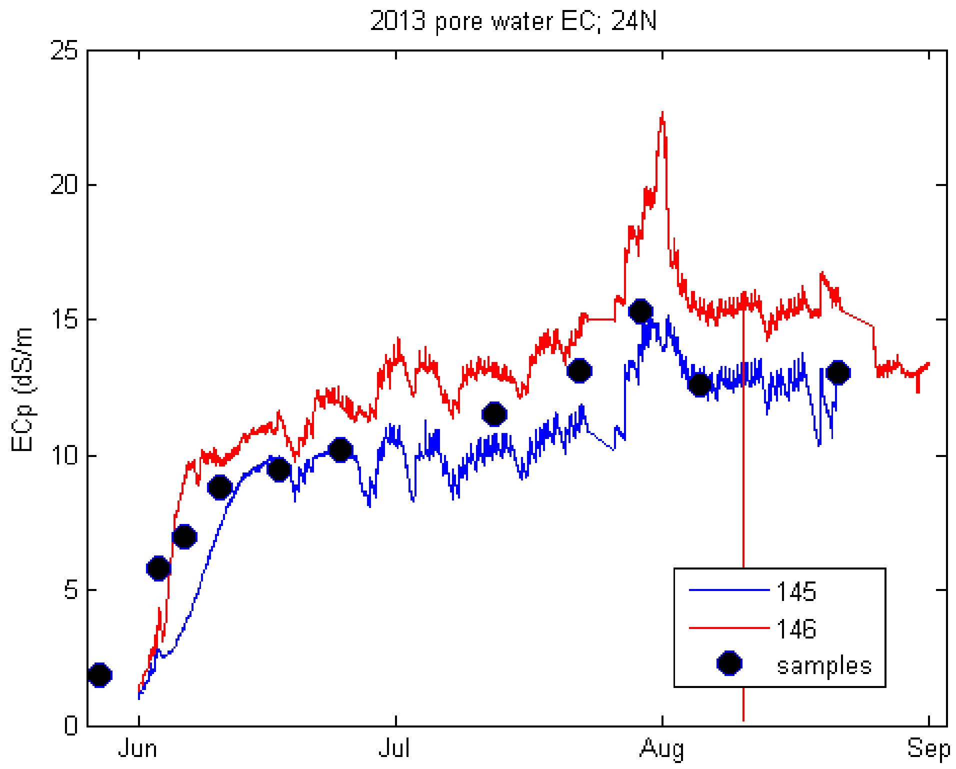


Figure 8a-c

Time trajectories of EC_p obtained from sensor EC_b via Eqn. (12), over the growing season in 2013 in fields with duplicate sensors, as well as suction cup samples, for fields 2Z, 8N, 24N. The irrigation treatment for each of these fields was 12 dS/m.

As the calibration equation Eqn (12) was derived from all sensor and suction cup samples together, the coincidence of the overall level is to be expected, but that it also works well for each of the fields individually is striking. It is also clear that two sensors in the same field may show different levels, but apart from the mutual bias the overall patterns are very similar between sensors. The increase in the beginning of the season is due to the start-up of the irrigation. Roughly two weeks are needed to get near the targeted concentration. It has to be noted that the pore water concentration may be higher or lower than the irrigation EC (12 dS/m in this case), depending upon the rainfall and evapo-transpiration. Currently, a further analysis is made with a simulation model based on mass balances, and preliminary results show that the observed behavior can, indeed, be related to these factors in relation to the irrigation.
It can once again be observed that fields with the same treatment may differ from each other. While in the 2012 experiments there was doubt whether this might be an artefact of the sensors, it is clear from the suction cup samples that the differences are real.

5 Discussion and conclusion

The laboratory calibration for VWC shows that the factory VWC validity range can be extended by making an adaptation at high EC_p (>10 dS/m) (Figure 2 and Eqn. 1).

The exercises with the laboratory EC data calibration show that it is not easy to make a laboratory EC calibration work in the field. The linear model derived directly from the data will not have general validity, as according to Figure 3 as well as the theory the pore water reconstruction will depend upon the volumetric water content. Moreover, errors in bulk sensor readings will be amplified when deriving pore water concentrations. Other difficulties are that theoretical relations require knowledge over the exact moisture content, which is not available in the field, thus creating another source of uncertainty. A calibration by direct comparison of sensor readings with soil water extracts offers better perspectives. However, in order to obtain a good field calibration that will be valid over a wide range of VWC's, it would be necessary to create such VWC's. As the current experiment – successfully - aimed at establishing well defined salinities by high irrigation, it is unlikely that accurate identification of VWC dependency is possible with the current data.

Nevertheless, in the moist conditions of the test facility, the sensor readings provide a useful and more detailed view of the behavior of the EC over time. In combination with the suction cup samples, and perhaps by sensor and field specific adjustment of the proportionality factor in Eqn. (12) it allows a realistic estimation of the pore water EC experienced by the root zone of the crop. The effect of differences between fields under the same treatment to assess crop tolerance might be counteracted by measuring the crop yields for each field separately.

Overall, it can be concluded that the sensors have clear added value to ensure the control of the root zone salinity over the growing season, and to compensate for weather influences. In combination with mass balance based simulation models it may open up exiting new ways of assessing tolerances of crop to salinity dynamics.

Acknowledgements

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