ORIGINAL PAPER

A model to formulate nutritive solutions for fertigation with customized electrical conductivity and nutrient ratios

J. M. Moreira Barradas[1] · B. Dida[2] · S. Matula[2] · F. Dolezal[2]

Abstract

Estimation of electrical conductivity (EC) in nutritive solutions is generally used to evaluate its suitability for irrigation. EC is a measure of osmotic potential of water applied via irrigation which affects growth and yield of irrigated crops. Generally, the estimation is achieved multiplying the total mass concentration by an empirical coefficient linearly relating it to EC. Different electrolytes with equal mass concentration induce different electrical conductivities which lead to inaccuracy when estimating EC of multiple salts in solution. The article presents the rationale and derivation of a model relating partial mass concentration (NSC) of several nutritive salts (NS) in solution to its resulting EC and ratio of nutritive elements (NE). Partial mass concentration of eight nutritive salts used in the composition of nutritive solutions has been co-related to resulting EC. Individual co-relations led to nonlinear regressions resulting in eight polynomial equations combined in a multivariable function describing EC in terms of NSC. Nutrient concentration NC (considering multiple NE in solution) and its resulting EC are described by a model relating them to NSC: $(\text{EC}, \text{NC}_1, \text{NC}_2, \ldots \text{NC}_n) = f(\text{NSC}_1, \text{NSC}_2, \ldots, \text{NSC}_n)$. The model estimates EC with considerable accuracy (co-relation of estimation vs. measurement—linear regression: $R^2 = 0.9986$) and integrates the fertigation decision support system—DSS-FS fertigation simulator. This provides a more effective and reliable method of estimating the EC which will, ultimately, impact management decisions.

Abbreviations

DO	Dissolved oxygen
DSS	Decision support system
DSS-FS	Decision support system-fertigation simulator
EC	Electrical conductivity
FEI	Fertigation Efficiency Index
NC	Nutrient concentration
NE	Nutritive elements
NER	Nutritive element ratio
NR	Nutrient ratio
NS	Nutritive salts
NSC	Nutritive salt concentration
P	Ratio of a given nutritive element in a given salt
SAR	Sodium adsorption ratio
TDS	Total dissolved salts
αα	An empiric coefficient also adopted by other authors to convert TDS to EC

✉ J. M. Moreira Barradas
joao.barradas@ist.utl.pt

[1] School of Energy, Environment and Agrifood, Cranfield University, Bldg. 52a Vincent First Floor, MK43 0AL Cranfield, Bedfordshire, UK

[2] Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamycka 129, 165 21 Prague 6, Suchdol, Czech Republic

Introduction

It is well established in the scientific literature that saline water in the root zone induces osmotic changes and directly affects nutrient uptake as Na^+-reducing K^+ uptake or by Cl^--reducing NO_3^- uptake (Cornillon and Palloix 1997; Halperin et al. 2003). Different plants show different symptoms and behavior during salt stress and other environmental stresses, for example, salt accumulation on the leaf reduces photosynthesis and growth (Sudhir and Murthy 2004). Therefore, it is important to consider the resulting salinity when planning nutritive solutions for irrigation (Moreira Barradas et al. 2014a, b). A common way of determining the concentration of salts in solution and its influence on the osmotic potential is to relate it to the resulting EC which can be measured resorting to conductometers.

The relationship between electrical conductivity (EC) and total dissolved solids (TDS) has already been modeled

by other authors resorting to linear regressions (American Public Health Association 1992; Abrol et al. 1988; USDA Salinity Laboratory Staff 1954). The concentration of total dissolved solids (TDS) (g/l) can be estimated when multiplying EC (dS/m) by an empirically determined coefficient (American Public Health Association 1992, standard method 2510) whose value has been determined and varies between 0.55 and 0.9. One of the most commonly used values for this coefficient is 0.64 (TDS = 0.64 EC). Although this adjustment is only valid for EC < 5 dS/m (Abrol et al. 1988; USDA Salinity Laboratory Staff 1954), it is acceptable for irrigation purposes as most of the crops are intolerant for EC above that limit.

Nutritive solutions are composed by multiple salts (say nutritive salts NS as they are sources of nutrients) with different influence on osmotic potential measured by the electrical conductivity. Therefore, a model was developed integrating information on the partial concentration of all different NS in solution—NSC (ppm). This new model aims to estimate the solutions resulting EC with higher level of accuracy than the estimation performed by other existing models while defining the nutrient ratio (NR). NR indicates a comparative proportion of nitrogen to phosphate to potash to other nutrients in solution. For example, a 15–10–5 fertilizer has a ratio N–P–K of 3–2–1, and a 0.08–0.012–0.04 nutritive solution has a ratio of 2–3–1.

The article being presented introduces the development of an empirical model to estimate electrical conductivity and necessary partial nutritive salt concentration NSC [NSC_1: NSC_n] for a desired nutrient ratio in solutions made up to n nutritive salts (NS_i) providing sufficient accuracy and precision for practical application, namely integrating decision support systems for fertigation management.

In Fig. 1 is shown the DSS-FS (Moreira Barradas et al. 2012) interface running the model described in this article. DSS-FS simulation allows estimating how different nutritive salts (injected into the irrigation water) modify an array of parameters such as: EC, pH, nutrient ratio, TDS, etc.

The article describes the DSS-FS algorithm used to accurately estimate the required partial concentration of each nutritive salt generate a desired nutrient ratio and EC of nutritive solutions. Other important indicators such as Fertigation Efficiency Index (FEI) (Moreira Barradas et al. 2012) and Sodicity SAR are also assessed by DSS-FS software.

Materials and methods

Electrical conductivity EC is defined as the reciprocal of resistivity ρ. It is expressed in Siemens per meter (S/m) usually at a reference temperature of 25 °C as temperature affects its magnitude (Eq. 1).

$$EC = \frac{1}{\rho}. \tag{1}$$

The electrical conductivity of a solution varies with the concentration of the electrolytes in it, however, this is not directly proportional, and therefore, the ions in the solution may have different abilities to transport electric current depending on the concentration in which they are present in the solution.

Fig. 1 DSS-FS interface for nutritive solutions formulation (Moreira Barradas et al. 2012)
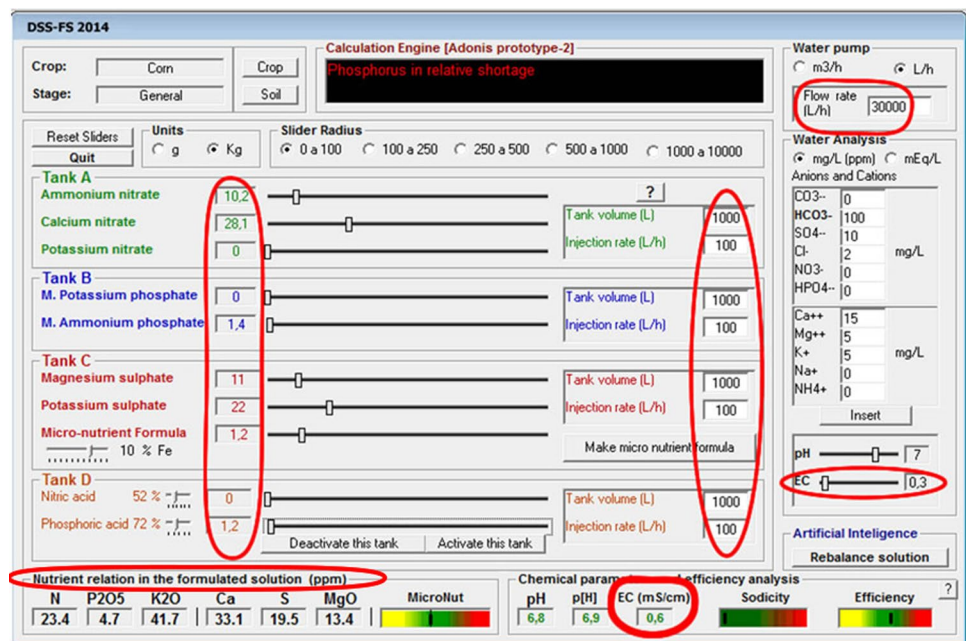
Therefore, the term molar conductivity Λ_m, (which is the ratio electrical conductivity k_i to molar concentration c_i — Eq. 2), appears to be very opportune as it describes the electrolyte's behavior when transporting electric current through a wide range of molarities in electrolyte solutions.

$$\Lambda_m \ = \ \frac{k_i}{Ci}. \tag{2}$$

According to the Debye-Hückel limiting law (see Eq. 3), it is easy to understand why the ions lose their ability to transport electric current with concentration.

$$\ln\left(\gamma_{\pm}\right) = \frac{A|z_+ z_-|\sqrt{I}}{1 \ + \ B \cdot d \cdot \sqrt{I}}, \tag{3}$$

where $\gamma_{\pm}$ mean activity coefficient of the ions in solution (–). A solvent-dependent constant ($A_{water} = -0.5085$). B electrolyte-dependent constant (–). I ionic strength (mol/l). z_+ ionic

charge of the cations (–). z_- ionic charge of the anions (–). d effective hydrated diameter of the ion in solution (Å).

The Ionic strength I is described by Eq. 4

$$I = \frac{1}{2} \sum_{i=1}^{n} c_i z_i^2, \tag{4}$$

with c_i molar concentration (mol/l). z_i ionic charge of the ions in solution (–).

The ionic activity a is the product of molar concentration c_i by the activity coefficient γ (Eq. 6)

$$a = \gamma c_i. \tag{5}$$

The relationship between γ and I (see Eq. 3) can be easily visualized in Fig. 2.

By the graph of Fig. 2, it is clear that ionic activity decreases with concentration. The individual ability of the ions to transport electric current follows the same pattern.

The considerations above relating molar conductivity to ionic activity are easily verified according to the nonlinear law for strong electrolytes proposed by Kohlraush (1875). The molar conductivity Λ_m is maximum at infinite dilution (Λ_m^o) and decreases with concentration c_i according to Eq. 6

$$\Lambda_m = \Lambda_m^o - K\sqrt{c}, \tag{6}$$

where K is the Kohlrausch coefficient, which depends mainly on the stoichiometry of the specific salt in solution and Λ_m^o the molar conductivity Λ_m at infinite dilution, also called limiting molar conductivity. This property explains why increments on salt concentration results in gradually smaller increments on EC.

The electrical conductivity of strong electrolytes increases with concentration but not linearly. For that reason, the rate of EC increment also decreases with concentration.
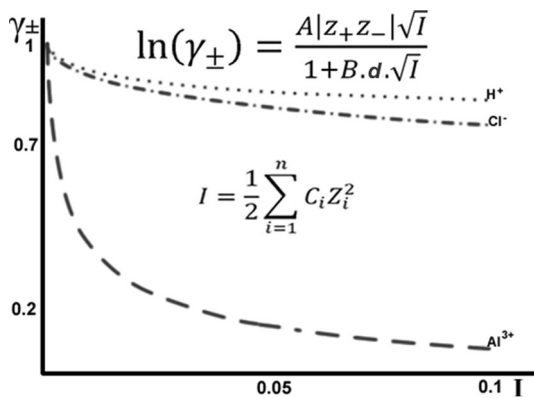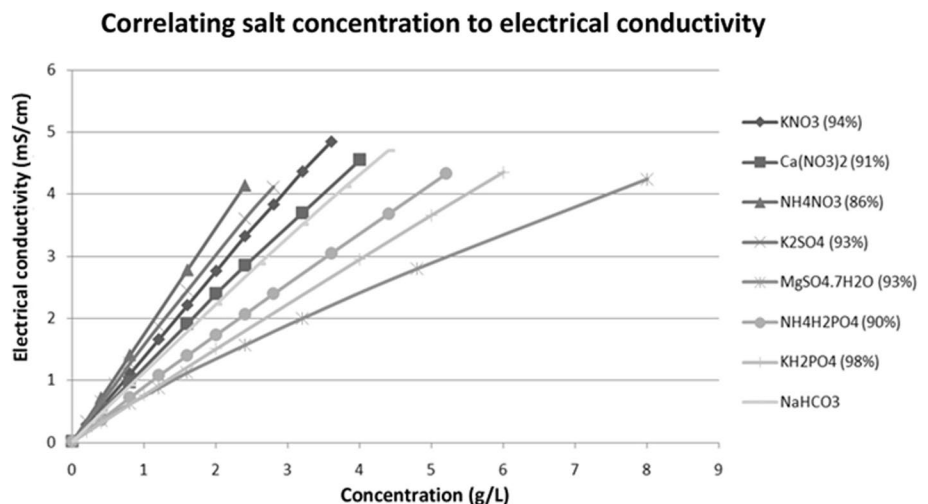

Fig. 2 Relation between the ionic activity coefficient $\gamma_{\pm}$ and ionic strength I for three different ions (H⁺, Cl⁻ and Al³⁺)

Fig. 3 Correlation between concentration and EC in eight different salts (Moreira Barradas et al. 2012)

Moreira Barradas et al. (2012) obtained a correlation between EC and concentration of different nutritive salts used in fertigation (Fig. 3).

Figure 4 shows a relationship between individual salt concentration and EC of eight electrolytes commonly used in fertigation. The results have been obtained resorting to a conductometer multi 350i (ion-selective electrode) which allows pH, EC (resolution: 1 μS/cm) and DO (dissolved oxygen) measurements with temperature compensation (Fig. 4).

The curves relating EC to concentration are linear at very low dilutions becoming polynomial with increasing concentration as shown by the polynomial equations of the curves in Fig. 4. These curves are represented by the general Eq. 7 when using the specific coefficients for each particular salt. These coefficients (see Table 1) were obtained from the analysis of the plot of concentration vs. EC shown in Fig. 4.

The additive property of anions and cations on resulting EC can be used to estimate with great accuracy the EC of a solution of several different salts based on an empiric solution.

It was possible to obtain eight nonlinear regressions from the plots shown in Fig. 4 (one regression for each curve) expressing a mathematical relationship between concentration and EC. This mathematical relationship is described by Eq. 7.

$$EC = aa_i NSC_i^3 + a_i NSC_i^2 + b_i NSC_i + c_i, \tag{7}$$

with NSC_i mass concentration (g/l) of nutritive salt i. aa-, a-, b- and c-specific salt coefficients (described in Table 1).

The equation described above and its coefficients have been linearly combined into Eq. 8, which describes the resulting EC of multiple electrolytes in solution.

$$EC = aa_f TDS^3 + a_f TDS^2 + b_f TDS + c_f. \tag{8}$$

With

$$TDS = \sum_{i=1}^{n} NSC_i. \tag{9}$$

The multi-electrolyte coefficients are given as follows:

$$aa_f = \frac{\sum_{i=1}^{n} aa_i}{TDS}, \tag{10}$$

$$a_f = \frac{\sum_{i=1}^{n} a_i}{TDS}, \tag{11}$$

$$b_f = \frac{\sum_{i=1}^{n} b_i}{TDS}, \tag{12}$$

$$c_f = \frac{\sum_{i=1}^{n} c_i}{TDS}, \tag{13}$$

$$^*TDS = \sum_{i=1}^{n} NEC_i, \tag{14}$$

*assuming the use of salts of only nutritive ions (NO_3^-;K^+; Ca^{2+} ; etc),

$$^{**}TDS = \sum_{i=1}^{n} NEC_i + \text{non nutritive elements}, \tag{15}$$

**assuming the use of salts of some non-nutritive ions such as Cl^- or bicarbonate $COOH^-$.

If the salts being used have no chlorides or no other non-nutritive elements in their composition, then the following equivalence is verified and TDS can also be related to the sum of array elements NEC[1: n]
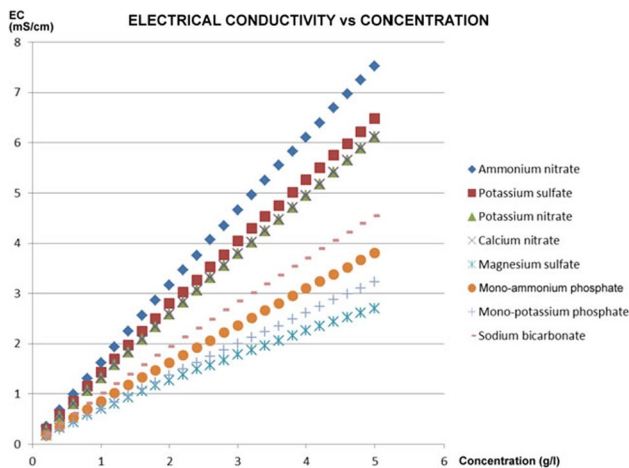

Fig. 4 Correlation between concentration (g/l) and resulting EC (mS/cm)

Table 1 Coefficients aa, a, b and c describing the mathematical relationship between concentration and EC of several electrolytes or nutritive salts individually in solution

Coeff.\salts	NH_4NO_3	K_2SO_4	KNO_3	$Ca(NO_3)_2$	$MgSO_4$	$NH_4H_2PO_4$	KH_2PO_4	$NaHCO_3$
aai	0.0009	0.0051	0.0042	0.0029	0.0039	0.0036	0.0024	0.002
ai	−0.029	−0.0658	−0.0524	−0.0496	−0.0545	−0.0404	−0.0282	−0.0338
bi	1.6238	1.4974	1.3823	0.9759	0.7082	0.8735	0.727	1.0279
ci	0.027	−0.0049	−0.0049	0.00005	0.0406	0.0125	0.001	0.0131

Table 2 System of six equations to six unknown describing six available nutritive salts NS[1:6] with different compositions and a desired nutritive solution expressed as partial concentration of six nutritive elements NE[1:6] present in each NS_i

Nutritive element (i)*	Composition of different nutritive salts (NS_i) in terms of mass percentages of nutritive elements (NE_i)						Required NEC_i (ppm)	Required nutritive element ratio NER_i (%)
	P_{ij} (%)							
	NS_1 (%)	NS_2 (%)	NS_3 (%)	NS_4 (%)	NS_5 (%)	NS_6 (%)		
NE_1: N	13	12	15	0	0	32	15	20
NE_2: P	0	61	0	0	0	0	5	6.67
NE_3: K	45	0	0	0	53	0	30	40
NE_4: Ca	0	0	21	0	0	0	10	13.33
NE_5: Mg	0	0	0	13	0	0	5	6.67
NE_6: S	0	0	0	18	18	0	10	13.33

(i)* Expressed as % of their oxides (K_2O, MgO and P_2O_5)

$$\sum_{i=1}^{n} NSC_i = \sum_{i=1}^{n} NEC_i. \tag{16}$$

The validity of Eq. 8, has been assessed by statistical analysis of 77 solutions of 8 different electrolytes randomly prepared. The NSC_i array ($i = \{1:8\}$) was defined in each solution resorting to EXCEL function "randbetween(0, 2)" with concentrations between 0 and 2 g/l and TDS < 5 g/l.

To plan a desired partial concentration $NEC_{[1:n]}$ of nutritive elements in solution implies an accurate estimation of $NSC_{[1:n]}$ of n salts in solution. Determining the correct array $NSC_{[1:n]}$ in solution for a desired array of concentrations of n nutritive elements $NEC_{[1:n]}$ can be trivially obtained formulating the problem with a system of equations (see Table 2). Table 2 is a system of six equations to six unknown represented by a quadratic matrix (6×6) showing six nutritive salts $NS_{[1:6]}$ with known composition expressed in mass percentages of six nutritive elements $NE_{[1:6]}$.

The fraction of NEC_i to TDS expresses the ratio of nutrients NER in solution (see Eq. 17)

$$NER_i(\%) = \frac{NEC_i}{TDS}. \tag{17}$$

Equation 18 describes NER* as a fraction of TDS not including the non-nutritive elements such as Cl^- or carbonates.

$$NER*_i(\%) = \frac{NEC_i}{\sum_{i=1}^{n} NEC_i}. \tag{18}$$

Crop demand for nutrients changes through the growing season (Hochmuth 2001). It is a common practice between fertigation professionals (Almeria–Spain and Estremadura region—west Portugal) to modify their nutritive solution formulations along the growing cycles of their crops. This happens because they usually identify different needs in terms of salts in solution by observing different plant nutritional deficiencies in different stages of the growing cycle when using a single nutritive solution (e.g., Hoagland solution or other variant).

The array NER*[1: n] describes the ratio of nutrients to each other in solution and evaluates the suitability of each particular formulation for different purposes of nutrient demand such as different stages of the phenologic cycle (vegetative development, blossom, fruit growth, fruit ripe, etc) independently of the absolute concentration TDS.

Table 2 shows the desired array of concentrations $NEC_{[1:6]}$ (ppm) and desired nutritive element ratio $NER_{[1:6]}$ (%). which relates NEC_i to TDS (see Eq. 17).

The percentage of NE_i in NS_j is given by P_{ij}.

$$\text{Where}: \begin{cases} NER_1 = \sum_{i=1}^{n} NSC_i \cdot P_{i1} \\ NER_2 = \sum_{i=1}^{n} NSC_i \cdot P_{i2} \\ NER_m = \sum_{i=1}^{n} NSC_i \cdot P_{im} \end{cases}. \tag{19}$$

Conversely, it will be necessary to estimate the necessary array of nutritive salt concentrations $NSC_{[1:n]}$ that generates the desired array of nutrient ratios $NER_{[1:6]}$ and their individual concentrations $NEC_{[1:6]}$ at a desired solution EC.

Using a case scenario with an array of available salts $NS_{[1:6]}$ and an array of required nutrient concentration $NEC_{[1:6]}$:

$NS_{[1:6]} = \{KNO_3; NH_4H_2PO_4; CaNO_3; MgSO_4; K_2SO_4; NH_4NO_3\}$.

$NEC_{[1:6]} = \{15;5;30;10;5;10\}$.

The values of $NSC_{[1:6]}$ are algebraically determined solving the system of equations (represented by the matrix

Table 3 Required $NSC_{[1:6]}$ for $NEC_{[1:6]}$ shown in Table 2 and $NER_{[1:6]}$

Composition of the nutritive solution in terms of required partial concentrations and ratios of salts

$NS_{[1:6]}$	$NSC_{[1:6]}$ (ppm)	$NER_{[1:6]}$ (%)
NS_1	46.5	20
NS_2	8.1	6.67
NS_3	47.6	40
NS_4	38.4	13.33
NS_5	17.09	6.67
NS_6	2.5	13.33
$TDS = \sum_{i=1}^{n} NSC_i^{a}$	160.19	100

[a]Total dissolved salts

shown in Table 2) resorting to a Cramer's rule (Gong et al. 2002).

See results in Table 3.

Formulating a nutritive solution with a specific EC and $NER_{[1:n]}$

Figure 5 shows an algorithm formulating a nutritive solution with specific EC and ratio of nutrients NER[1:n] iteratively resorting to Eq. 8 combined with an empirical correlation TDS to EC.

The inputs are the desired EC, NER[1: n] and available fertilizers NS[1: n] for the formulation.

The output is the array of concentrations of n fertilizers NSC[1: n] required to generate the specified inputs: EC and NER[1: n].

Considering the array of concentrations of the required salts in solution NSC as a function of NER and EC: NSC[1: n] = f{EC; NER[1: n]}.
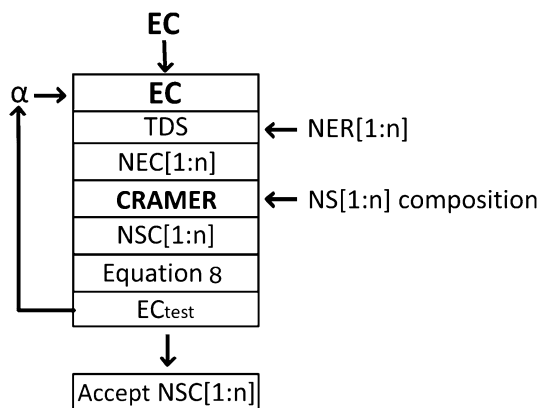

Fig. 5 NSC[1: n] defined as a function of NER[1: n] and EC using α to approximate the result as a starting point of the iteration

Let α (an empiric coefficient also adopted by other authors to convert TDS to EC) be set as α = 0.64 and ε (the error defined for estimation) customized as ε = 0.01.

1　Fisrt step of iteration:

1.1 TDS = α.EC

1.2 NEC[1:n] = NER[1:n].TDS

1.3 NSC[1:n] is solved applying a Cramer's rule to a system of equations as shown in tables 2 and 3, equations relating a desired array NEC[1:n] in solution to available salts and their composition in terms of nutrients - NSC[1:n]= f{EC;NER[1:n]}

2　Second step of iteration:

2.1 TDS = $\sum_{i=1}^{n} NSC_i$

2.2 EC_{test} = f(NSC[1:n]) by equation 8.

2.3 ΔEC=EC_{test}-EC

2.4 If ΔEC > ε then:　Restart step 1.1 with α = α + 0.1ε

2.5 If ΔEC < -ε then:　Restart step 1.1 with α = α - 0.1ε

2.6 If |ΔEC| < ε then:　**accept NSC[1:n] given by step 1.3 as the result.**

Desired EC and NER[1: n] is given by step 2.6 of the iteration with NSC[1:6] in solution.

Results and discussion

The resulting EC was both measured using a conductometer Multi 350i and estimated through Eq. 8. Afterwards, a correlation between measured and estimated results was created to verify the accuracy of the estimation based on the coefficient of determination R^2.

The groups of observed and estimated EC were compared through a t test and an analysis of variance (ANOVA single factor) for an interval of confidence of 95%.

Figure 6 shows the correlation measured vs. estimated EC by the proposed methodology (Eq. 8).
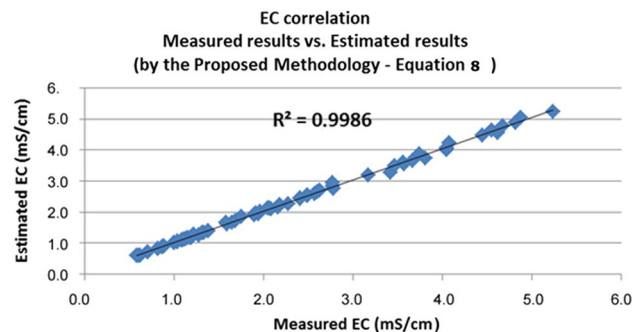

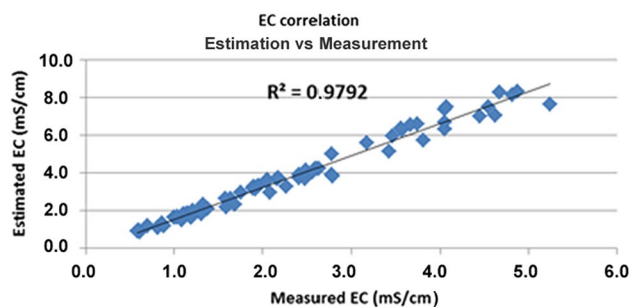**Fig. 6** Correlation estimation (Eq. 8) vs observation

Fig. 7 Correlation estimation (Abrol et al. 1988) and many others vs. measured results

The correlation above shows a considerably high accuracy of estimation resorting to Eq. 8.

Figure 7 shows the correlation between the observed results and estimation according to Abrol et al. (1988). This methodology has been adopted by several authors (USDA Salinity Laboratory Staff 1954; American Public Health Association 1992).

The analysis of variance (ANOVA single factor for 95% interval of confidence) performed between the estimated values using the proposed methodology described by Eq. 8 and the measured values shows that we can assume no differences between the estimation and the observation when using the proposed methodology. These differences are to be considered when using the methodology proposed by other authors—Abrol et al. (1988), USDA Salinity Laboratory Staff (1954), American Public Health Association (1992)—Table 4 shows that the null hypothesis is to be rejected in this case.

A correlation based upon multiple regressions using EXCEL statistical analysis was also performed with a R^2 of 0.9986, however, its coefficients are only valid within the experimental set and cannot be used to estimate random combinations outside the experimented scenario where the estimation via Eq. 12 is still valid.

EC estimated via statistical regression will be given by Eq. 20 with X[1:8] (corresponding to NSC[1:8]) and coefficient[1:8] as shown in Table 5, however, valid only inside the experimented scenario as opposed to Eq. 8 valid also in any random combination outside the experimented scenario.

$$EC = \sum_{i=1}^{8} \left(X \text{ variable}_i \cdot \text{coefficient}_i \right). \tag{20}$$

The EC correlation of measured results and estimation via statistical regression is given by Fig. 8.

RMSE and NRMSD were also used to evaluate the performance of the model as opposed to the one proposed by other authors.

Table 6 shows RMSE and NRMSD between estimation (by Eq. 8 vs other authors) and the observation.

Practical application

The algorithm described in this paper integrates the decision support system—DSS-FS Fertigation Simulator (Moreira Barradas et al. 2012). Data from farms where the DSS-FS software was used as the primary consulting system has been analysed. The results were presented by (Moreira Barradas et al. 2014a, b) proving this system to be user-friendly and a valuable tool to increase production in considerable amounts, saving 20–30% in input factors and energy as reported by the majority of users (Moreira Barradas et al. 2014a, b).

Sustainability

The effects of fertigation using the DSS-FS Fertigation Simulator on soil health parameters were also assessed by Moreira Barradas et al. (2014a, b). Physicochemical properties of a Haplic Chernozem soil were measured while applying fertigation in natural grassland during the growing season in a hemiboreal climate with irrigation management based on the DSS-FS model. There has been no evidence of soil degradation in any of the parameters where this study was focused. This does not imply that the use of other methods to estimate resulting EC (namely the empirical relation proposed by the USDA) is harmful. Nevertheless, the proposed methodology introduces a more accurate technique integrating an algorithm also able to formulate customized nutritive solutions.

Conclusion

Using a simple correlation factor (0.64 as the most commonly used value) shows the null hypothesis rejected after analysis of variance (ANOVA) with also a considerable high RMSE result (RMSE = 1.632; NRMSD = 0.3479).

Equation 8 (proposed in this work) is an empirical solution with a considerable level of accuracy and precision (R^2 = 0.9982; ANOVA—acceptance of null hypothesis for an interval of confidence of 95%; RMSE = 0.054; NRMSD = 0.0115), that is particularly interesting to be used when relating EC to mass concentration. It also shows itself a convenient solution when operating non-pure electrolytes (fertilizers) where reassessment of individual coefficients aa, a, b and c might be a necessity from time to time.

Therefore, the algorithm proposed in Fig. 5 integrating Eq. 8 has been demonstrated as an extraordinary tool (when

Table 4 Relation between EC and partial concentration of eight nutritive salts (randomly defined), measured using a conductometer Multi 350i, estimated by Eq. 8 and also by the methodology adopted by Abrol et al., USDA Salinity Laboratory Staff, American Public Health Association (APHA) and other authors (first 16 measurements)

| NSC$_1$ (g/l) | NSC$_2$ (g/l) | NSC$_3$ (g/l) | NSC$_4$ (g/l) | NSC$_5$ (g/l) | NSC$_6$ (g/l) | NSC$_7$ (g/l) | NSC$_8$ (g/l) | TDS (g/l) | EC (mS/cm) Multi 350i | EC (mS/cm) Eq. 8a | APHA and others EC = TDS/ 0.64 |
NH$_4$NO$_3$	K$_2$SO$_4$	KNO$_3$	Ca(NO$_3$)$_2$	MgSO$_4$	NH$_4$H$_2$PO$_4$	KH$_2$PO$_4$	NaHCO$_3$	Total	(measured)	(estimated)	(estimated)
0.9	0.2	0.5	0.6	0.8	0.5	0.2	0.1	3.7	3.8	3.7	5.8
0.1	0.9	0.1	0.6	0.6	0.9	0.7	0.2	4.0	3.6	3.5	6.3
0.5	0.8	0.9	0.9	0.7	0.4	0.1	0.4	4.5	4.6	4.5	7.0
0.5	0.6	0.0	1.0	0.8	0.9	0.0	0.4	4.2	3.7	3.9	6.6
0.4	0.9	0.8	0.5	0.5	0.2	1.0	0.3	4.5	4.5	4.5	7.0
0.5	0.6	1.0	0.5	0.8	0.6	0.7	0.5	5.3	4.9	5.0	8.3
0.6	0.1	0.9	0.3	0.5	0.2	0.6	0.9	4.0	4.1	4.0	6.3
0.6	0.1	0.4	0.4	0.1	0.1	1.0	0.8	3.3	3.4	3.3	5.2
0.1	0.7	0.9	0.4	0.8	0.1	0.7	0.7	4.3	4.1	4.0	6.7
0.4	0.3	0.1	0.4	0.8	0.2	0.7	0.7	3.6	3.2	3.2	5.6
0.1	0.0	0.1	0.1	0.1	0.2	0.3	0.3	1.1	1.0	1.0	1.7
0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.8	0.7	0.7	1.3
0.1	0.2	0.2	0.2	0.3	0.1	0.2	0.2	1.4	1.4	1.4	2.2
0.1	0.0	0.1	0.2	0.2	0.1	0.0	0.2	0.9	0.9	0.9	1.4
0.1	0.2	0.2	0.2	0.2	0.1	0.3	0.2	1.3	1.3	1.3	2.0
0.0	0.2	0.1	0.1	0.1	0.2	0.1	0.0	0.6	0.6	0.6	0.9

[a]Estimated using the coefficients described in Table 1

Table 5 ANOVA single factor performed between observed values and estimated values using the proposed methodology and also the methodology proposed by other authors—Abrol et al. (1988), USDA Salinity Laboratory Staff (1954), American Public Health Association (1992)

ANOVA (single factor)					
Source of variation	SS	*df*	MS	*F*	*p* value	*F* crit
Performed between the observed and the estimated values using Eq. 8						
Between groups	70.39425	1	70.39425	22.05183	5.89E−06	3.903366
Within groups	485.2171	152	3.192218			
Total	555.6113	153				
Source of variation	SS	*df*	MS	*F*	*p* value	*F* crit
Performed between the observed and the estimated values using the methodology suggested by other authors						
Between groups	70.39425	1	70.39425	22.05183	5.89E−06	3.903366
Within groups	485.2171	152	3.192218			
Total	555.6113	153				
	SS	*df*	MS	*F*	Significance *F*	
Performed between the observed and the estimated values obtained by regression statistics						
Regression	157.2732	8	19.65914	1.97E+32	0	
Residual	6.77E−30	68	9.96E−32			
Total	157.2732	76				
	Coefficients	Standard error	*t* Stat	*p* value	Lower 95%	Upper 95%
Parameters of the model obtained by regression statistics						
Intercept	0.11361	7.36E−17	1.54E+15	0	0.114	0.114
X variable 1 (NSC$_1$)	0.727893	2.34E-−16	3.11E+15	0	0.728	0.728
X variable 2 (NSC$_2$)	0.331112	1.61E−16	2.05E+15	0	0.331	0.331
X variable 3 (NSC$_3$)	1.488617	1.63E−16	9.11E+15	0	1.489	1.489
X variable 4 (NSC$_4$)	1.947041	1.02E−16	1.91E+16	0	1.947	1.947
X variable 5 (NSC$_5$)	0.633355	2.18E−16	2.90E+15	0	0.633	0.633
X variable 6 (NSC$_6$)	0.550849	1.87E−16	2.94E+15	0	0.551	0.551
X variable 7 (NSC$_7$)	1.197413	1.82E−16	6.59E+15	0	1.197	1.197
X variable 8 (NSC$_8$)	0.334546	2.26E−16	1.48E+15	0	0.335	0.335
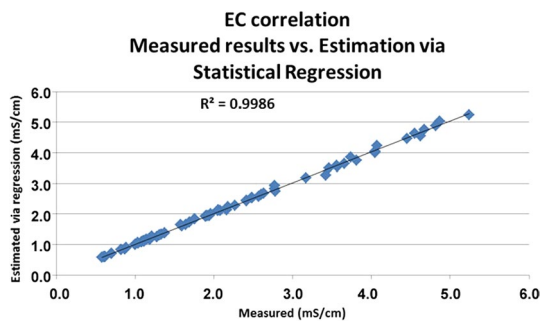
Fig. 8 Correlation estimation (via statistical regression) vs. measured results

Table 6 Model performances for RMSE and NRMSD

MODEL	RMSE	NRMSD
Other authors[a]	1.632	0.3479
Equation 8	0.054	0.0115

[a]Abrol et al. (1988), USDA Salinity Laboratory Staff (1954), American Public Health Association (1992)

integrating DSS) to formulate nutritive solutions having a specified value of EC and a desired nutrient ratio according to an array NS[1:N] of available fertilizers (Table 5).

References

Abrol IP, Yadav JSP, Massoud FI (1988) Salt-affected soils and their management. FAO Soils Bulletin No. 39. FAO Roma

American Public Health Association (1992) Standard methods for the examination of water and wastewater. 18th edn, Washington, DC

Cornillon P, Palloix A (1997) Influence of sodium chloride on the growth and mineral nutrition of pepper cultivars. J Plant Nutr 20:1085–1094

Gong Z, Aldeen M, Elsner L (2002) A note on a generalized Cramer's rule. Linear Algebra Appl 340:253–254. https://doi.org/10.1016/S0024-3795(01)00469-4

Halperin ST, Gilroy S, Lynch JP (2003) Sodium chloride reduces growth and cytosolic calcium, but does not affect cytosolic pH, in root hairs of *Arabidopsis thaliana* L. J Exp Bot 54:1269–1280

Hochmuth G (2001) Nutrient solution formulation for hydroponic (Perlite, Rockwool and NFT) tomatoes in Florida, nutrient solutions. North Florida Research and Education Center, Suwannee Valley, Live Oak

Kohlrausch F (1875) Law of independent ionic mobilities. Ann Phys. 156. 601–618. Leipzig

Moreira Barradas JM, Matula S, Dolezal F (2012) A decision support system-fertigation simulator (DSS-FS) for design and optimization of sprinkler and drip irrigation systems. Comput Electron Agric 86:111–119

Moreira Barradas J, Abdelfattah A, Matula S, Dolezal F (2014a) Effect of fertigation on soil salinization and aggregate stability. J Irrig Drain Eng https://doi.org/10.1061/(ASCE)IR.1943-4774.0000806, (05014010)

Moreira Barradas J, Matula S, Dolezal F, Mekonnen GB, Mihalikova M, Chala AT (2014b) Practical application of DSS-FS fertigation simulator in several crops world wide. Irr Drain. https://doi.org/10.1002/ird.1832/full

Sudhir P, Murthy SDS (2004) Effects of salt stress on basic processes of photosynthesis. Photosynthetica 42:481–486

USDA Salinity Laboratory Staff (1954) Diagnosis and improvement of Saline and Alkali Soils. Handbook 60, USDA, Washington DC, p 160