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# Electrical Conductivity Measurements in Agriculture: The Assessment of Soil Salinity

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Additional information is available at the end of the chapter

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## Abstract

Soil salinity is an important issue constraining the productivity of irrigation agriculture around the world. The standard method for soil salinity assessment is based on a laboratory method that is cumbersome and gives rise to limitations for data-intensive works. The use of sensors for the assessment of the apparent electrical conductivity (EC) of soils offers a way to overcome these constraints. These sensors are based on three electromagnetic phenomena, namely, electrical resistivity, electromagnetic induction, and reflectometry. Each class of sensors presents its own advantages and drawbacks. In the following chapter, these are presented along with the most popular commercial EC sensors used in nowadays agriculture, equations for the assessment of soil salinity on basis sensor measurements, some examples of application, and present and future development trends.

**Keywords:** electrical conductivity, soil salinity, agriculture, irrigation, electrical resistivity, electromagnetic induction, time domain reflectometry, amplitude domain reflectometry, frequency domain reflectometry

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## 1. Introduction

Soil salinity is the concentration in the soil pore water of major dissolved ions. These are mainly  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ , and in some instances also  $\text{CO}_3^{2-}$ . In agricultural lands,  $\text{K}^+$  and  $\text{NO}_3^-$  also become major ions and thus, significantly contribute to salinity. All these ions build up in soils as a consequence of both evaporation and plant transpiration, which extracts almost pure water from soils while leaving its salts behind, and also as a consequence of fertilization practices. As soil salinity increases, the potential of the soil pore water decreases, thus obliging plants to overcome an increasingly high energy gap for soil water uptake. Additionally,

various ions, e.g.,  $\text{Na}^+$ ,  $\text{Cl}^-$ , may also cause specific toxicity effects on plants, impair their nutritional balance, and/or decrease the permeability of soils with further indirect deleterious effects on crops. The development of these stressful conditions poses a remarkable threat for the sustainability of agriculture, mainly under irrigation. Of the world cultivated land, which amounts to roughly 1500 Mha, about 340 Mha, i.e. 23%, is salt affected [1]. Soil salinization has been estimated to cause income losses of about 12 billion US\$ per year globally [2]. In order to cope with soil salinity and the soil salinization issue, reliable and fast techniques for water and soil salinity evaluation are needed. The rigorous assessment of soil salinity requires, first, the extraction of representative samples of the soil pore water, and second, the subsequent determination of the concentrations of the aforementioned ions at a standard soil water content for their eventual summation in a single parameter known as total soluble salts (TSSs). Although rigorous, this method is expensive, labor-intensive, soil-destructive, and results-deferred, therefore posing severe constraints for data-demanding works both in space and time.

The carrying out of electrical conductivity (EC) measurements offers a way to overcome some of the limitations of the sampling and laboratory method. Specifically, the second part consisting in the analytical determinations of the major ion contents in the soil pore water can be replaced by one single measurement of EC, thus remarkably decreasing work and expenses in the laboratory, and shortening the obtaining of data. This methodological change has been globally so successfully adopted, that nowadays the standard for soil salinity assessment is the EC at 25°C of soil extracts at water saturation, in this chapter abbreviated as  $\text{EC}_{e,25}$ . Besides, since not only the soil pore water conducts electricity, but also the bulk soil, its apparent electrical conductivity ( $\text{EC}_a$ ) can be used as a proxy for the assessment of soil salinity. However, some caution is in order when using  $\text{EC}_a$  in this regard, because  $\text{EC}_a$  depends on other soil properties, importantly water content, texture, structure, and mineralogy, in addition to salinity itself, therefore complicating the interpretation of measurements [3]. Furthermore, the soil  $\text{EC}_a$  can be measured by means of various different techniques, which are based on i) potential drop or electrical resistivity (ER), ii) electromagnetic induction (EMI), and iii) reflectometry, either time (TDR), amplitude (ADR), or frequency (FDR) domain. These techniques and the corresponding sensors feature different abilities to sample soils for  $\text{EC}_a$  measurements and therefore give rise to  $\text{EC}_a$  values that present differences.

In this chapter, the foundations of the EC techniques nowadays available for the assessment of soil salinity in agriculture will be presented, along with the specific models developed to make estimations of soil salinity. The main commercial sensors used to make measurements of EC in agricultural soils will be presented, too, commenting on their strengths and weaknesses. Examples of the practical application of sensors for soil salinity assessment in agriculture will be given. Finally, we will try to envisage the future trends in the development and applications of this technology.

## 2. Electrical conductivity

The cause of the electrical conductance is the existence of particles with electric charge which, from a microscopic point of view, are loosely bound to specific positions within materials and

thus, are capable of conveying electric charge. The materials featured by these particles are able to conduct electricity and thus are known as conductors. Liquid water is a conductor because under natural conditions, it contains dissolved ions which are movable charged particles. Soil, the other material that concern us here the most, is a composite conductor in which water, solid particles, and air are present in variable quantities and arrangements, and in which the electric charge carriers are water dissolved and solid particle loosely adsorbed ions. These ions are, specifically, the major inorganic ions in the aqueous systems of the earth crust, i.e., cations  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ , and  $\text{K}^+$ , and anions  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$  and  $\text{NO}_3^-$ .

When waters or soils are exposed to no electric fields, ions move randomly within, and macroscopically no net electric current is observed. On the contrary, when an electric field is applied, cations move to lower potentials whereas anions move to higher ones, and therefore, the water or soil system conducts electricity. The EC ( $\sigma$ ) features the proportionality factor between the current density ( $\mathbf{J}$ ,  $\text{A/m}^2$ ) and the electrical field ( $\mathbf{E}$ ,  $\text{V/m}$ ):  $\mathbf{J} = \sigma \mathbf{E}$  and thus, it measures the increment of the electric current through each unit area of a surface perpendicular to its flowing direction per unit increase of an externally applied electric field. Therefore, the EC of a material is a physical quantity that indicates its ability to conduct electric current. It is the reciprocal of the material's resistivity ( $\rho$ ):  $\sigma = 1/\rho$ , and its units in the SI are the  $\text{S m}^{-1}$ .

### 3. Standard EC for soil salinity assessment

The EC of soil materials measured as such is known as bulk or  $\text{EC}_a$  ( $\sigma_a$ ) because the measured EC corresponds to an EC-equivalent homogeneous single-phase material [3]. Even more important is to note that  $\text{EC}_a$  is different from the EC of the soil pore water ( $\text{EC}_p$  or  $\sigma_p$ ), i.e. the EC of the soil solution separated from the soil solids. The convenient way of soil salinity estimation using EC instead of chemical analysis would involve the measurement of  $\text{EC}_p$ . However, such direct measurement of  $\text{EC}_p$  is never made because, on the one hand, of a practical issue, and on the other hand, of the need for standardization.

From a practical point of view, representative samples of the soil solution at usual field soil water contents are difficult or impossible to obtain [4]. Besides, soil salinity continuously varies as so does the soil water content, thus demanding a specific soil water content for standardization. By international agreement, the standard soil water content for salinity assessment is soil water saturation. On the one hand, water saturation is the lowest soil water content from which a sample of the soil solution can be easily obtained and, on the other hand, water saturation is the highest soil water content attainable under field conditions and thus, representative of the soil salinity to which plants are exposed. Therefore, the universal standard for soil salinity appraisal is the EC of the soil saturation extract at  $25^\circ\text{C}$  [5], which is abbreviated as  $\text{EC}_{e,25}$  in this chapter. The salt tolerance of all crops is expressed in terms of  $\text{EC}_{e,25}$  [6, 7], and therefore, in agriculture, all measurements obtained with whichever other method have to be converted to  $\text{EC}_{e,25}$  in order to be useful for soil salinity assessment. All  $\text{EC}_{e,25}$  data are obtained through the preparation of saturated pastes by equilibration of a disturbed soil sample with deionized water, sampling of the aqueous phase by vacuum extraction, and eventual EC measurement [8]. To correctly interpret  $\text{EC}_{e,25}$  values in soil studies and agriculture, various

environmental factors must be taken into account and specifically for agriculture, the salt tolerance of available crops must be known. Since interpretation of  $EC_{e,25}$  is not within the scope of this chapter, the interested reader is led to [5] and [9].

#### 4. Temperature effects on EC

As indicated, in soil studies and agriculture, EC data have to be expressed at a standard temperature of 25°C. This is because the EC of all materials depends on temperature. Specifically, the EC of waters and also soils increases as temperature increases. Thus, unless the temperature of all waters and soils is adjusted to 25°C by equilibration in thermostatic baths, all measurements must be corrected to 25°C. This is done by measurement of the temperature (T) of the material under test, and subsequent application of an adequate equation to convert from EC at T ( $EC_T$  or  $\sigma_T$ ) to EC at 25°C ( $EC_{25}$  or  $\sigma_{25}$ ). The function that relates EC with T depends on the specific salt composition, i.e. on the concentration of every major ion in solution. Since the sum of all ion concentrations is exactly what we estimate through the EC measurement, an empirical function is needed to assess  $EC_{25}$  from  $EC_T$ . There are two functions in major use for this assessment provided T is between 3 and 50°C. The ratio model (Eq. 1) is based on the EC evolution of KCl 0.01 M solutions with temperature, while the exponential model (Eq. 2) was developed by [5] by taking EC measurements on different soil saturation extracts and various salt solutions at different temperatures [10, 11]:

$$\sigma_{25} = \frac{\sigma_T}{1 + 0.0191(T - 25)} \quad (1)$$

$$\sigma_{25} = \sigma_T \left( 0.4470 + 1.4034e^{-T/26.815} \right) \quad (2)$$

The use of empirical equations has a practical consequence in that the difference between true and corrected  $EC_{25}$  depends on T, and this difference decreases as T is closer to 25°C, being null at T = 25°C. Therefore, the EC measurements must be taken as close to 25°C as possible to avoid this empirical bias; usually, a range of  $25 \pm 5^\circ\text{C}$  is enough to have differences under 1% in most instances. This warning extends to all EC measurements in soil studies and agriculture either in waters or soils.

#### 5. EC measurement methods

EC measurements in soil studies and agriculture can be readily made with various types of sensors based on different electromagnetic phenomena which are classified into i) ER, ii) EMI, and iii) reflectometry, either TDR, ADR, or FDR.

### 5.1. Electrical resistivity (ER)

When an electric field is applied to a piece of a conductor, and current develops, the system is featured by resistance  $R = l/(\sigma A)$ , where  $l$  and  $A$  are, respectively, the length and the cross-sectional area of the piece of material under test. On basis, the inverse proportionality between  $\sigma$  and  $R$ , measurement of EC can thus be done by measuring the resistance of a piece of soil or water of known dimensions. Modern ER measurements are taken by using alternating currents (ACs) of extremely low to super low frequencies, usually below 30 Hz. At low frequencies, i.e. below 1 MHz, capacitance and electrolytic effects on the measurement electrodes and besides, amplifier distortions, are avoided, while resistive effects overwhelmingly contribute to the signal like in a purely direct current (DC) measurement [12, 13].

Nowadays, the simplest device to measure EC is a digital ohmmeter, which is composed of a probe made of a pair of metal electrodes, a power supply able to provide a standard constant current ( $I_{std}$ ) to the electrodes and the soil in-between, and a voltmeter able to measure the potential drop across ( $\Delta V$ ). Thus, the soil resistance is simply calculated applying the Ohm's law as  $R = \Delta V/I_{std}$ , and hence EC as

$$\sigma = kI_{std} / \Delta V \quad (3)$$

where  $k = l/A$  is known as the cell constant of the probe. The cell constant depends on the probe design, it has units of reciprocal of length, and can be analytically assessed in some simple cases.

In soil studies and agriculture, all EC measurements in waters, including irrigation waters and soil extracts such as the saturation extract, are taken by means of ER using laboratory bench or handheld conductimeters. These instruments are calibrated with EC standards to determine their cell constant. In agriculture most EC values lay in the range between 0.01 and 1.6 S m<sup>-1</sup> which, in order to take unbiased measurements, determines both the EC of the standards needed for calibration and the appropriate cell constant of the instrument. For agricultural applications, the EC standards cover two orders of magnitude, usually with specific EC values of 0.0147, 0.1413, and 1.288 S m<sup>-1</sup> at 25°C, which correspond to aqueous solutions 0.001, 0.01, and 0.1 M in KCl, whereas the appropriate cell constants are around 1 cm<sup>-1</sup>.

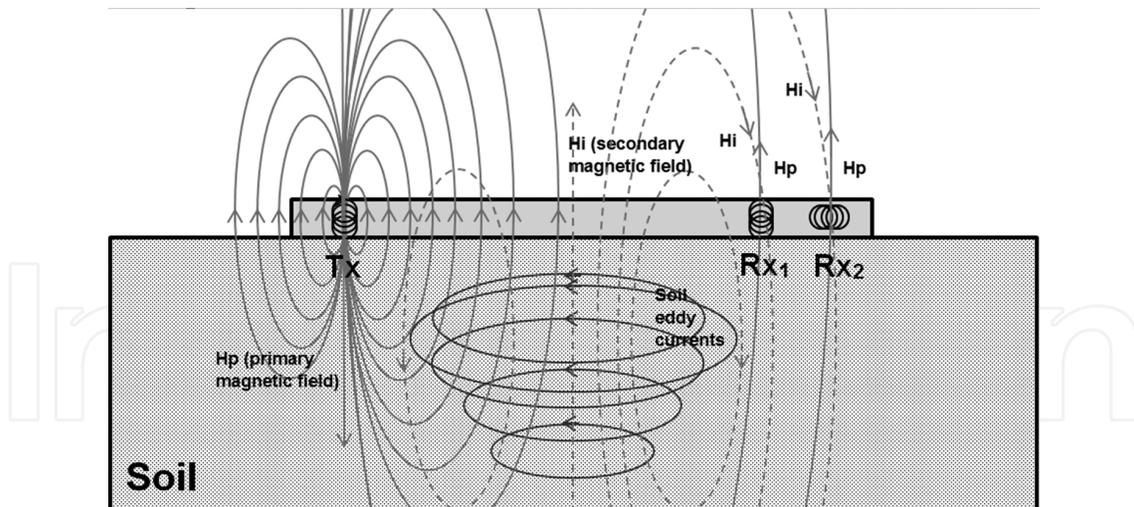
The two-point ER method just presented has some constraints that are revealed as non-negligible when the method is used for soils. This is because the two-point ER method not only measures the conductor's resistance but also the resistance of the probe electrodes and wiring and besides, is altered by the Galvani potential difference that develops across the contacts of the electrodes with the conductor. To overcome these limitations, the four-point method developed by [14] for geophysics sounding is used instead of the simple two-point method.

Contrary to the two-point method, in which the potential drop is measured with the same electrodes used to inject the current into the soil, in the four-point method, each function is carried out with its own pair of electrodes. By using separate electrodes, neither the electrodes resistances, nor the contact resistances between the metal electrodes and the soil show up in

the measured EC, thus making interpretation of data more straightforward. The electrodes can be arranged according to various configurations, which differ in geometry and electrode spacing [15].

## 5.2. Electromagnetic induction (EMI)

The  $EC_a$  of soil materials can be estimated with no contact by means of EMI. In EMI instruments, there is one transmitting (Tx) and one or more receiving ( $Rx_1$ ,  $Rx_2$ , etc) coils (**Figure 1**). The Tx is connected to an oscillator operating at very low frequencies (VLF), specifically in the range between 1 and 100 kHz in which the conductivity soil response has been found to be almost independent from frequency [16]. This way, the Tx generates a primary time variable magnetic field ( $H_p$ ). By the EMI phenomenon, this time variable magnetic field induces a varying electric field in the soil and in response, many alternating eddy currents are generated within. The amplitude of the total alternating electric current is proportional to i) the EC of the soil, ii) the rate of change of the primary magnetic field ( $H_p$ ), and iii) the orientation and proximity of the instrument to the soil. The ACs generated in the soil lead in turn, by the same EMI phenomenon, to the creation of a secondary magnetic field ( $H_i$ ). The resulting total magnetic field ( $H_p + H_i$ ) induces again, by the same EMI phenomenon, a current in the receiver(s) coil(s) of the instrument. The amplitude of the quadrature-phase of this total field (real component) is the one which is related to a depth-weighted soil EC ( $EC_a^*$ ) [17]. Importantly, note that  $EC_a^*$  is different from  $EC_a$ . This signal is amplified and formed into an output voltage, which is shown as such  $EC_a^*$  value to the user [18].



**Figure 1.** Schematic overview of the functioning of an EMI sensor, specifically the DUALEM-1 in which one receiving coil is coplanar ( $Rx_1$ ) and the other is perpendicular ( $Rx_2$ ) to the transmitting coil (Tx).

## 5.3. Reflectometry

Reflectometry is based on the effects soil has on primary alternating electric currents transmitted into the soil via embedded electrodes. In reflectometry, the characteristics of ACs

change in response to the dielectric properties of the soil medium, and therefore other alternating signals are generated. These secondary signals are recorded, and their speed, amplitude, or frequency are analyzed, thus giving rise to three different techniques. These are two genuine reflectometry methods such as TDR and ADR, in addition to FDR, which is based on the electrical resonance of RLC circuits.

Reflectometry  $EC_a$  measurements are based on the fact that conductivity is one of the main mechanisms through which electromagnetic signals transmitted into the soil lose energy. This energy loss is represented by the imaginary part of the soil dielectric permittivity which is conveniently represented by a complex frequency-dependent variable:  $\epsilon^*(f) = \epsilon'(f) - j \epsilon''(f)$ , where  $j = \sqrt{-1}$  is the imaginary unit, and  $\epsilon'(f)$  and  $\epsilon''(f)$  are, respectively, the real and imaginary parts of  $\epsilon^*$ . The real part of permittivity represents energy storage and is mainly, but not only, related to the soil water content ( $\theta$ ,  $m^3/m^3$ ) because of the remarkably higher relative dielectric permittivity of pure water (80) regarding soil solids (3–5) and soil air (1). The imaginary part of permittivity depends on various energy loss mechanisms such as dipole relaxation ( $\epsilon_{rel}''(f)$ ) and importantly  $EC_a$  through:

$$\epsilon''(f) = \epsilon_{rel}''(f) + \frac{\sigma_a}{2\pi f \epsilon_0} \quad (4)$$

where  $\epsilon_0 = 8.85418 \cdot 10^{-12}$  F/m is the vacuum permittivity. In reflectometry,  $EC_a$  is assessed from energy losses usually assuming that the other loss effects encompassed in  $\epsilon_{rel}''(f)$ , are negligible regarding the conductivity loss, i.e.  $\sigma_a/2\pi f \epsilon_0$ . Since frequency similarly affects both  $\epsilon_{rel}''(f)$  and  $\sigma_a/2\pi f \epsilon_0$ ,  $EC_a$  measurements will be barely affected by frequency changes. On the contrary, the assessment of  $\theta$  is made on basis the apparent permittivity ( $\epsilon_a$ ), which depends on both energy storage and loss:

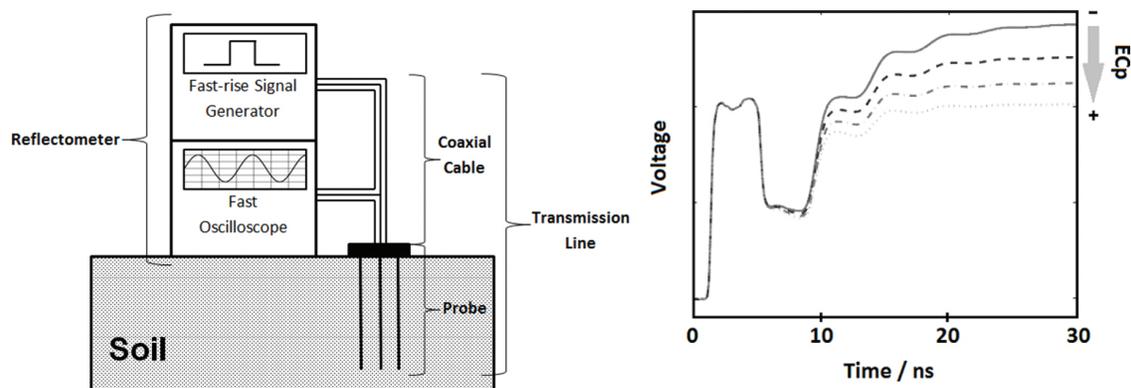
$$\epsilon_a = \frac{\epsilon'(f)}{2} \left[ 1 + \sqrt{1 + \tan^2 \left( \frac{\epsilon''(f)}{\epsilon'(f)} \right)} \right] \quad (5)$$

As a result, since energy losses decrease as frequency increase,  $\epsilon_a$  approaches the real permittivity ( $\epsilon'$ ) as frequency increases and therefore, as frequency increases  $\theta$  estimations will be more accurate.

### 5.3.1. Time domain reflectometry (TDR)

TDR is a broadband high-frequency technique originally applied to soil studies as a means for the in situ fast estimation of  $\theta$  [19]. Reflectometry in the time domain is based on the reflection primary precisely timed electrical pulses undergo when sent along a transmission line (TL) ending in various electrodes inserted into the soil. The three essential parts of a TDR instrument are i) a TL which is formed, in turn, by a coaxial cable ending in a probe formed by two-four metal rods, ii) a fast-rise signal generator operating at high frequencies between 0.02 and 3

GHz, and iii) a fast oscilloscope (**Figure 2** left). The oscilloscope is fast enough to sample the voltage level of the TL at intervals down to around 100 ps and, hence, obtain the TDR waveform [21] (**Figure 2** right). This way, the fast-rise electromagnetic pulse composed of a wide range of frequencies transmitted to the TL is partially reflected back and forth at the end and at the beginning of the TL giving rise to an electromagnetic oscillation whose voltage amplitude is sampled. The main characteristics of the primary and reflected pulses that are useful in this regard are i) traveling back and forth velocity and ii) attenuation. The first characteristic is related to  $\epsilon_{ar}$  and thus mainly to  $\theta$ , whereas the second one is mainly related to just the imaginary part of permittivity and thus to  $EC_a$  [22, 23]. The voltage at late time (**Figure 2** right) is usually used to derive the  $EC_a$  by means of the Giese and Tiemann equation [24] as indicated in [25]. However, in practice, several different voltage values in the TDR attenuation curve can be reliably used and therefore, various different equations have been proposed to calculate  $EC_a$  from TDR waveforms [26, 27].



**Figure 2.** Schematic diagram of a TDR instrument (left) and graph showing the attenuation effect of soil salinity on TDR waveforms after [20] (right).

### 5.3.2. Amplitude domain reflectometry (ADR)

Reflectometry in the amplitude domain is another genuine reflectometry technique like TDR. Similar elements to those previously described for TDR equipment are used for ADR. In ADR, however, the measurement is based on the amplitude features of the standing electromagnetic oscillation in different parts of the TL [28]. Besides, since in ADR the signal generator operates in a frequency range between 10 and 100 MHz, i.e. significantly lower than in TDR, instrumentation prices decrease.

### 5.3.3. Frequency domain reflectometry (FDR)

Contrary to TDR and ADR, FDR is not based on the analysis of reflected electromagnetic pulses but on the resonance features of RLC circuits in which a capacitor is formed by two electrodes and the in-between and surrounding soil. The RLC circuit in FDR instruments is formed by a signal generator, plus resistor, inductive and capacitive elements, including the lossy capacitor involving the soil (**Figure 3**). This lossy capacitor is characterized by a resistance ( $R_1$ ) and a

capacitance ( $C_1$ ) which depends, in addition to the soil, on its specific design and  $\epsilon_a$  according to  $C_1 = g\epsilon_a$ , where  $g$  is the capacitor design factor in length units. The soil sensing capacitor is connected in parallel with the parasitic capacitance due to the circuit board and connections ( $C_2$ ), and in series with the circuit board which is characterized by a well-known capacitance ( $C_3$ ) [29, 30]. Therefore,  $g$  and  $C_2$  are instrument-specific, and even sensor-specific, and their values must be obtained by calibration using liquids of known dielectric properties.

In FDR, the signal generator operates at frequencies below TDR, which are in the range from 10 to 200 MHz. At these relatively low frequencies,  $\epsilon_a$  measurements are more dependent on other soil properties in addition to  $\theta$  and therefore, FDR is less reliable than TDR for  $\theta$  estimations [31]. In FDR instruments, the frequency of the AC is usually varied within a narrow range until resonance is achieved in the circuit, i.e., until amplitude is maximum. The resonant frequency depends mostly on  $\epsilon_a$ , while the amplitude depends mostly on  $EC_a$ . Therefore, in FDR, the  $EC_a$  is assessed from the amplitude at resonance [12].

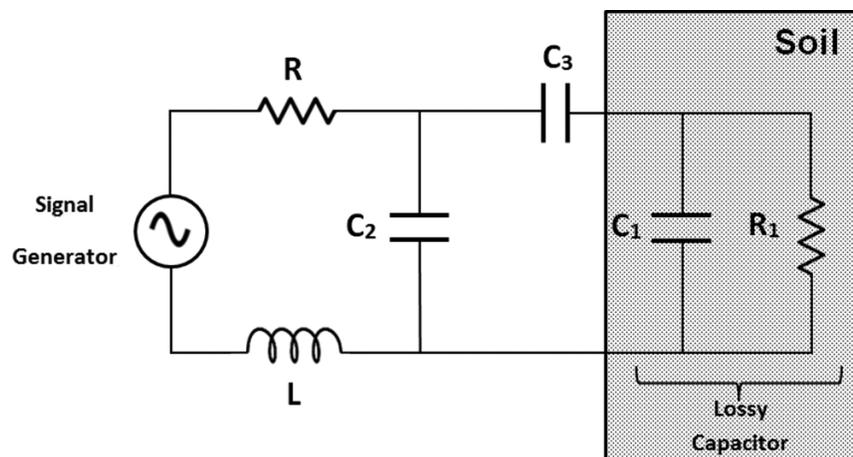


Figure 3. Circuit diagram for a single-probe FDR sensor.

## 6. Assessment of soil salinity from EC measurements

As indicated in Section 3,  $EC_{e,25}$  is the standard for soil salinity assessment; however, the method of the saturation extract is labor-intensive and soil-destructive. To overcome either one or both of these drawbacks, several alternative methodologies have been proposed. These methodologies can be grouped into two classes: i) those based on more readily prepared soil water extracts and ii) those based on  $EC_a$  measurements. The first class of methods constitute alternative sampling and laboratory methods and will not be dealt with in this chapter. The interested reader is referred to the literature on the subject, e.g. [32] and references therein.

In the second class of methods, the interpretation of  $EC_a$  measurements is made by means of models relating  $EC_a$  with  $EC_{e,25}$ . Unfortunately, universally valid equations do not exist for this transformation. Such relationship must be assessed almost in every instance by using two

different methods. The first one consists of two steps: i) the assessment of  $EC_p$  from  $EC_a$  and then ii) the assessment of  $EC_e$  from  $EC_p$ . The second one is based on the assessment of  $EC_e$  directly from  $EC_a$ . Each of these methods presents its own advantages and drawbacks.

### 6.1. Two-step estimation of $EC_e$ from $EC_a$

The first part of this method, i.e. the calculation of  $EC_p$  from  $EC_a$ , is based on what is known about how soils behave as conductors. In the second part,  $EC_e$  is related to  $EC_p$  either through modeling of soil solution dilution and concentration processes, or by means of empirical equations.

#### 6.1.1. First step: estimation of $EC_p$ from $EC_a$

Since soils are composite materials made of solids, water, and air, electric charge is conveyed through them by means of three different paths acting in parallel [33]. These are i) a continuous liquid pathway in which dissolved ions are the charge carriers, ii) an alternate solid-liquid pathway in which both exchangeable and dissolved ions are the charge carriers, and iii) a pathway formed by solid particles in direct and continuous contact with one another in which exchangeable ions are the charge carriers. Since just the continuous liquid (i) and continuous solid pathways (iii) can be straightforward parameterized as separate units, the following equation with just two summands representing, respectively, the continuous liquid plus continuous solid pathways, can be used to model  $EC_a$  as a function of soil properties [34]:

$$\sigma_a = \theta(a\theta + b)\sigma_p + (a\theta + b)B\rho_bCEC \quad (6)$$

In Eq. 6, the alternate liquid-solid pathway is somewhat included into both summands,  $(a\theta + b)$  is a factor known as tortuosity or transmission coefficient where  $a$  and  $b$  are fitting parameters which depend on soil texture and structure,  $B$  is the equivalent conductance of the counterions on the soil exchange complex ( $S\ m^2/mmole_C$ ),  $\rho_b$  is the soil bulk density ( $kg/m^3$ ), and finally,  $CEC$  is the soil cation exchange capacity ( $mmole_C/kg$ ), which depends on soil texture, clay mineralogy, and organic matter content. In Eq. 6, there are three soil-specific parameters ( $a$ ,  $b$ , and  $B$ ) that must be assessed by calibration by taking several  $EC_a$  measurements and analyzing the soil for  $\theta$ ,  $EC_p$ ,  $\rho_b$ , and  $CEC$ . Once the parameters ( $a$ ,  $b$ , and  $B$ ) of Eq. 6 have been calibrated,  $\sigma_p$  can be isolated to estimate the EC of the soil solution by means of Eq. 7.

$$\sigma_p = \frac{\sigma_a - (a\theta + b)B\rho_bCEC}{\theta(a\theta + b)} \quad (7)$$

In addition to the model parameters, an adequate estimation of  $EC_p$  from  $EC_a$  by means of Eq. 7 requires knowing the values of  $\rho_b$ ,  $CEC$ , and  $\theta$  in the same soil volume. The former two ( $\rho_b$ ,  $CEC$ ) can be assumed to be barely spatial and overall time variable and thus, as steady soil

properties for many applications. On the contrary, the soil water content ( $\theta$ ) is usually very variable both in space and time and can virtually never be considered as steady for survey and monitoring applications. Therefore, to correctly estimate  $EC_p$  from  $EC_a$  measurements,  $\theta$  must be determined along with  $EC_a$  in the soil volume under test. This determination could rigorously be done by sampling of the measured soil volume and subsequent laboratory analysis. However, this direct method would override most of the advantages gained by working with  $EC_a$  sensors. To overcome this limitation, the soil water content could either be estimated by means of the various nowadays available indirect sensing techniques such as i) neutron thermalization, ii) gamma ray attenuation, iii) those related to soil thermal properties, and iv) electromagnetic methods [35]. Nevertheless, the first three methods provide  $\theta$  estimations not for the same soil volume surveyed by the  $EC_a$  sensor but for an adjacent soil volume, thus giving rise to errors. With electromagnetic methods and specifically with reflectometry, the requirement of  $\theta$  estimations in exactly the same soil volume under test has been addressed because most of these instruments can measure  $EC_a$  in addition to estimate  $\theta$ . For use with such instruments, various simple empirical equations have been proposed to assess  $EC_p$ . Eq. 8 uses the empirical linear relationship that has been revealed to exist between  $\sigma_a$  and  $\varepsilon_a$  as the water content changes while  $EC_p$  is kept constant, to assess  $EC_p$  on basis just  $EC_a$  and  $\varepsilon_a$  sensor measurements [36]:

$$\sigma_p = \frac{\sigma_a - \sigma_s}{m(\varepsilon_a - \varepsilon_{ss})} \quad (8)$$

where the parameters  $\sigma_s$ ,  $\varepsilon_{ss}$  can be interpreted, respectively, as the particle surface EC, and the soil solids dielectric permittivity. They both along with  $m$  have to be assessed by calibration and depend on soil properties such as texture, mineralogy, and organic matter. Note that in Eq. 8, and other models,  $EC_p$  estimations are expected to improve provided  $\varepsilon_a$  is replaced by  $\varepsilon'$  [37], and that temperature corrections are still pending. The Hilhorst [38] model (Eq. 9) constitutes a simplified version of Eq. 8, where just one parameter, i.e. the soil dielectric permittivity at zero  $EC_a$  ( $\varepsilon_{\sigma_a=0}$ ), is needed, and  $\varepsilon_w(T)$  is the dielectric permittivity of water, whose value depends just on temperature.

$$\sigma_p = \frac{\sigma_a \varepsilon_w(T)}{\varepsilon_a - \varepsilon_{\sigma_a=0}} \quad (9)$$

Provided the relatively low variability of  $q_b$  and CEC regarding  $\theta$ , a simpler version of the model represented by Eq. 7 has been developed for assessing  $EC_p$  along with the use of instruments capable of both  $EC_a$  measurements and  $\theta$  estimations [39]:

$$\sigma_p = \frac{\sigma_a - \sigma_s}{(a\theta + b)\theta} \quad (10)$$

where  $\sigma_s$  is a lumped coefficient, i.e., equal to the second summand  $((a\theta + b) B Q_b \text{ CEC})$  in Eq. 6, representing the particle surface EC, and  $\theta$  is usually empirically assessed with a third-order polynomial of the form:  $\theta = a_3 \varepsilon_a^3 + a_2 \varepsilon_a^2 + a_1 \varepsilon_a + a_0$  [19]. An alternative to this polynomial is the simplified dielectric mixing (SDM) model, which is more theoretically based [40]. Thus, the following equation (Eq. 11), which combines Eq. 10 with the SDM model has been proposed to estimate  $EC_p$  at 25°C ( $\sigma_{p,25}$ ) from sensor measurements of  $EC_a$ ,  $\varepsilon_a$  and T [41]:

$$\sigma_{p,25} = \frac{\sigma_a h(T) - \sigma_s}{\left[ a \frac{-b_0 + \sqrt{\varepsilon_a}}{b_1} + b \right] \left[ \frac{-b_0 + \sqrt{\varepsilon_a}}{b_1} \right]} \quad (11)$$

where  $h(T) = \sigma_{25}/\sigma_T$  is a function of temperature as given by the ratio (Eq. 1) or the exponential model (Eq. 2).

### 6.1.2. Second step: estimation of $EC_e$ from $EC_p$

Once  $EC_p$  has been estimated by means of the previous equations, it can be related to  $EC_e$  by means of either process-based or functional models, or even a mixture of both. The process-based models simulate the dilution of the soil solution from the field water content at which measurements have been taken ( $\theta_f$ ) to the soil saturation water content ( $\theta_s$ ). This model can be as simple as a dilution ratio giving rise to the following estimation:  $EC_{e,25} = (\theta_f Q_{bs} EC_{p,25}) / (\theta_s Q_{bf})$ , where  $Q_{bs}$  and  $Q_{bf}$  are the bulk densities of, respectively, the saturated paste and field soil [42, 43], or either a complex model such as SALSOLCHEMEC [44], that requires, in addition to  $\theta$  and  $Q_b$  data, the likely major ion contents and CEC of the soil. These complex models, though more accurate, can be regarded as less appealing because they require more data and further elaboration of results. The functional models, on the contrary, are based on the statistical relationship between  $EC_{e,25}$  and  $EC_{p,25}$ , which must be obtained by calibration beforehand. A mixture of both approaches can be applied considering the dilution ratio to calculate a proxy of  $EC_{e,25}$ , i.e.  $EC_{e,25}'$ , whose statistical relationship with the true  $EC_{e,25}$  must also be obtained by calibration beforehand. Nevertheless, an advantage of this latter approach over the purely statistical one is that estimation errors will diminish.

## 6.2. One-step estimation of $EC_e$ from $EC_a$

$EC_e$  can be directly estimated from  $EC_a$  measurements using purely empirical calibrations. Most of these calibrations have been developed to interpret the  $EC_a$  measurements taken with ER and EMI techniques. Calibrations are usually obtained by multiple linear regression (MLR), principal components regression (PCR), partial least squares regression (PLSR), or either kriging (KR) or co-kriging regressions (CKR). Regardless of the specific regression technique, in these models, a profile  $EC_e$  average can be assessed as a mathematical function of several  $EC_a$  sensor measurements, e.g. vertical and horizontal configuration EMI measurements ( $EC_{a-v}^*$ ,  $EC_{a-h}^*$ ), in addition to an n number of soil properties ( $P_1, P_2, \dots, P_n$ ) including other sensor measurements, coordinates, micro-topography features, etc:

$$EC_e = h(\sigma_{a-v}^*, \sigma_{a-h}^*, \dots, P_1, P_2, \dots, P_n) \quad (12)$$

Profile  $EC_e$  averages are not the only data we can obtain with the use of these techniques. With many ER and certainly most EMI instruments we have got the ability to delineate the one-dimensional (1D) soil  $EC_a$ , and therefore, we can elaborate on calibrations for  $EC_e$  variations along the soil vertical coordinate.

## 7. Commercial sensors for measuring EC

### 7.1. Electrical resistivity sensors

ER gives rise to the simplest of techniques for the assessment of  $EC_a$  in agriculture with essentially two classes of ER systems: static and mobile instruments. Two-point ER measurements can be done with commercial handheld digital multimeters (DMM, DVOM). Provided the length (L), radius (r), and spacing (d) between the pair of test leads driven into the soil are known  $EC_a$  can be measured by less than 50 €. However, two-point ER measurements are usually made with sensors specifically developed for soil applications. The capacitance-conductance (CC) combined 5TE and GS3 sensors by Decagon (Decagon Devices, Inc., Pullman, Washington, USA) provide  $EC_a$  measurements using ER. Besides, both sensors also measure  $\varepsilon_a$  through capacitance, which is the simplest sensor technique for  $\theta$  estimation, and T through a thermistor in roughly the same soil volume, and are worth between 200 and 300 €. Subsequent elaboration of  $EC_a$ ,  $\varepsilon_a$ , and T data with the equations in Section 6 along with equations in Section 4 allows for the assessment of  $EC_{p,25}$ .

In the 1970s, a four-point ER probe based on a Wenner's array was developed by Rhoades and van Schilfgaarde [45]. On basis of this design, various commercial devices were developed next in order to make discrete and continuous  $EC_a$  measurements in agriculture [33]. The Martek (Martek Instruments, Raleigh, North Carolina, USA) soil salinity sensors adequately served for both profile soundings and continuous burial measurements. Models such as the SCT-10 included a temperature sensor, and thus provided both raw and temperature corrected readings for improved data interpretation. The commercialization of this sensor was discontinued by Martek Instruments; however, a very similar device including temperature measurement can still be bought from Eijkelkamp (Giesbeek, The Netherlands) for roughly 4500 €.

Since the works of Wenner, the static four-point ER sensors early evolved to mobile  $EC_a$  instruments [46]. Nowadays, there are instruments sold by Veris (Veris Technologies, Inc., Salina, Kansas, USA), in which sensors take the shape of coulter-mounted in a trailer that is towed by a vehicle through the field under test. These instruments are worth between 12,000 and 24,000 €, and integrate global positioning system (GPS) and data-logging utilities. Besides, the newest Veris models (V2000XA, V3100, V3150) present two pairs of potential measurement electrodes instead of just one, which jointly enable a simple soil profiling of  $EC_a$  with two depths. The coulter electrodes are also sold individually and therefore users can build their own craft ER sensor systems [47].

The most critical issues in order to make reliable  $EC_a$  measurements with ER sensors are i) knowing accurately the probe cell constant value and ii) assuring good contact between all the electrodes and the soil. The cell constant can be analytically assessed in most instances as shown in ref. [48]. This is the only option when performing four-point measurements with mobile systems. However, for most applications with commercial two-point and four-point static sensors, the probe cell constant is empirically assessed by means of calibration using EC standards (Section 5.1).

## 7.2. Electromagnetic induction sensors

The EMI instruments most commonly used in nowadays agriculture include the DUALEM-1, DUALEM-2, and DUALEM-21 (Duaem, Inc., Milton, Ontario, Canada); the EM38, EM38-DD, and EM38-MK2 sensors (Geonics Ltd., Mississauga, Ontario, Canada), and the Profiler EMP-400 (Geophysical Survey Systems, Inc., Salem, New Hampshire, US). The simplest EMI instruments are the EM38 and the DUALEM-1, in which there are just one transmitting and one or two receiving coils 1 m apart, and are worth between 11,000 and 14,000 €. As a consequence, these instruments are sensitive to the soil  $EC_a$  down to a depth between 0.5 and 1.5 m, which is where most plant's roots develop and thus, the most interesting for soil studies and agriculture.

The soil depth response to EMI instruments depends on the separation and orientation of transmitting and receiving coils, and on their distance over ground in the following ways: i) as the separation between both coils increases, the soil depth contributing to the sensor signal increases; ii) when one coil, either the transmitter or the receiver, is turned from vertical to horizontal, the soil depth contributing to the sensor signal decreases; and iii) as the height over ground increases, the soil depth contributing to the sensor signal decreases.

The EM38 presents two parallel coils and measurements can be performed with both coils either vertical (V-V) or horizontal (H-H) to the soil. When the sensor is laid onto the soil, 70% of the cumulative sensor signal is provided by the upper 1.55 m in the V-V orientation, and by the upper 0.75 m in the H-H orientation. The DUALEM-1 presents three coils, one transmitter and two receivers (**Figure 1**). While the transmitter coil is vertically oriented, one receiver is 1 m apart and parallel to the transmitter (vertical orientation), and another is 1.1 m apart and perpendicular to the transmitter (horizontal orientation). When the sensor is laid onto the soil, 70% of the cumulative sensor signal is provided by the upper 1.5 m in the V-V orientation, and by the upper 0.5 m in the V-H orientation. As described, two  $EC_a^*$  measurements can be made with both the EM38 and DUALEM-1 sensors. Both measurements can then be elaborated to have qualitative information about how  $EC_a$  changes with soil depth. For example, if the V-V  $EC_a^*$  ( $EC_{a-v}^*$ ) is higher than the H-H or V-H  $EC_a^*$  ( $EC_{a-h}^*$ ), it is because  $EC_a$  increases with soil depth. On the contrary, if  $EC_{a-v}^*$  is lower than  $EC_{a-h}^*$ , it is because  $EC_a$  decreases with soil depth. Even though the EM38 and DUALEM-1 sensors work at slightly different frequencies, which are, respectively, 14.7 and 9 kHz, both provide the same data for  $EC_{a-v}^*$  and  $EC_{a-h}^*$  and can then be used interchangeably [49].

The EM38-DD is an evolution of the EM38, in which two EM38 sensors are bolted together and electronically coupled. Besides, one is vertically and the other horizontally oriented, so as to

have simultaneous  $EC_{a-v}^*$  and  $EC_{a-h}^*$  measurements. The EM38-MK2 is a further evolution of the EM38 in which there are two receiving coils instead of just one. The receivers are parallel to the transmitter and, respectively, 0.5 and 1.0 m apart from it and, as a consequence, to have 70% of cumulative sensor signal, between 0.75 and 1.55 m are required in the V-V-V orientation, and between 0.4 and 0.75 m are required in the H-H-H orientation [50].

In the DUALEM-2, the separation between the transmitter and receivers has been doubled to be 2 m and, as a consequence, the depth for 70% cumulative signal is 3 m in the V-V orientation and 1 m in the V-H orientation. The DUALEM-21 is a combination of the previous DUALEM-1 and DUALEM-2 in which one pair of receivers are 1 m away from the transmitter, and another pair of receivers are 2 m away. This configuration allows DUALEM-21 users to have four depths of simultaneous  $EC_a$  sounding.

An instrument similar to the EM38 and the DUALEM-1 is the EMP-400, in which there are just two parallel coils, one transmitter and one receiver separated by 1.22 m to take measurements in the V-V or H-H orientations. The EMP-400 is a multi-frequency instrument able to take measurements at whichever three frequencies between 1 and 16 kHz; however, to have  $EC_a^*$  measurements similar to those provided by similar EMI instruments, users have to work at 15 kHz. The EMP-400 is worth roughly 16,000 €.

All the aforementioned EMI instruments can be used along with data-logging and positioning systems (GPS) to have georeferenced and continuous  $EC_a^*$  measurements. In fact, DUALEM instruments and Profiler EMP-400 present internal GPS receivers [50]. Dualem also sells the sensors of their instruments individually under denominations 1S, 2S, etc., to allow practitioners to build their own customized equipment.

### 7.3. Reflectometry sensors

ER instruments provide  $EC_a$  measurements, while EMI instruments provide  $EC_a$  estimations through  $EC_a^*$ . However, since  $EC_a$  strongly depends on  $\theta$  in addition to soil salinity, and secondarily on other soil properties, reliable estimations of  $EC_p$  require, at least, a reliable estimation of  $\theta$  in the soil volume under test. With maturing of reflectometry techniques, reliable estimations of both  $\theta$  and  $EC_a$  can be made in exactly the same soil volume, giving rise to effective  $EC_p$  estimations [22, 51]. Another advantage of reflectometry is that contact between soil and electrodes is important but not so critical than with ER.

#### 7.3.1. Time domain reflectometry sensors

Nowadays, there are three types of TDR measurement systems. The first type consists of four parts: i) a compact reflectometer that includes a signal generator, a fast oscilloscope, and a microcontroller; ii) one datalogger; iii) one or more multiplexors; and iv) several TDR probes that can be monitored at once. A remarkable example of an affordable compact reflectometer with wide multiplexing capabilities is the TDR100 (Campbell Scientific Inc., Logan, Utah, USA) which is worth 4000 €, and 100 € more per probe. Another modern example of this kind of instruments is the Trase Systems (SoilMoisture Equipment Corp., Santa Barbara, California, USA). With these TDR measurement systems, the  $EC_a$  and  $\theta$  calculations can be programmed

to be made by the reflectometer, or either the TDR traces can be saved and calculations deferred. All these instruments are essentially research oriented.

There are even more compact instruments which constitute a second type of TDR systems. These instruments integrate reflectometer and probe and besides, a temperature sensor. Examples are the Trime-PICO 64/32 (Van Walt Ltd., Haslemere, Surrey, UK), which works at 1 GHz, and the CS615 and CS616 (Campbell Scientific Inc., Logan, Utah, USA), which operate at frequencies of 45 and 70 MHz, respectively [52], and thus are less expensive (less than 300 €) but also less accurate for  $\theta$  estimation than the previous more complex TDR systems. These compact TDR probes make  $EC_a$  and  $\theta$  calculations automatically and are adequate for practical applications in agriculture and soil studies.

A third type of TDR systems are profile probes. These devices are formed by several paired electrodes, which are usually equally separated on opposite sides of a non-conductive tube, which is vertically inserted into the soil. Examples are the Trime PICO-Profile (IMKO Micro-modultechnik GmbH, Ettlingen, Baden-Württemberg, Germany), and the Vector Probe (Aquaspy, San Diego, California, USA) with 12 sensors down to 1.2 m depth, which is worth less than 1000 €.

### 7.3.2. Amplitude domain reflectometry sensors

There are several commercial ADR sensors able to estimate  $\theta$  such as the popular Theta Probe (Delta-T Devices Ltd., Cambridge, UK). However, to our knowledge, only the Hydra Probe (Stevens Water Monitoring Systems, Inc., Portland, Oregon, USA) is able to take both  $\epsilon_a$  and  $EC_a$  measurements. This sensor forms its probe with three aligned stainless steel prongs, wired to an oscillator working at 50 MHz. It also measures soil temperature and is worth roughly 400 €.

### 7.3.3. Frequency domain reflectometry sensors

Commercial FDR sensors work at frequencies between 10 and 200 MHz, i.e. lower than TDR. There are two basic types of FDR sensors: single and profile probes. The degree in which the soil contributes to the dielectric medium in the soil sensing capacitors is markedly different in each kind of probe. For single-probe devices, the soil forms a good deal of the dielectric medium (**Figure 3**), while in profile probes, the soil medium is just an almost marginal part of it. In profile FDR probes, the soil sensing capacitors are attached to a non-conductive rod or plate which is introduced into an insulating access tube, and this in turn vertically into the soil. Therefore, the soil sensing capacitors are not in contact with the soil, and in fact only a small part of the electromagnetic field created by each one permeates the surrounding soil. This fringe field extinguishes rapidly from the capacitor. Accordingly, most of the sensitivity of FDR profile probes lies in the soil zone immediate adjacent to the access tube, which is the one more affected by soil drilling, thus raising concerns about representativeness [53].

There are several single-probe FDR instruments for both  $\theta$  and  $EC_a$  estimations. One of the most used for agricultural applications is the WET sensor (Delta-T Devices Ltd., Cambridge, UK), which is worth roughly 1200 €. The WET sensor forms the soil sensing capacitor by means

of three aligned 6-cm-long metal prongs, with the central rod acting as the plus plate, and the side prongs acting as the ground plates of the capacitor. Additionally, the WET sensor has a thermistor at the central rod tip that enables soil temperature measurements. Measurements of  $EC_a$  with the WET sensor are very similar to those carried out with ER techniques. However, the relatively low oscillation frequency in the WET sensor (20 MHz) makes  $\epsilon_a$  measurements much too dependent on soil salinity and therefore, impairs the estimations of  $\theta$ , and thus  $EC_p$  [41].

Although there are several commercial profile FDR instruments for  $\theta$  estimations, to our knowledge, only the TriSCAN (Sentek Pty Ltd., Stepney, South Australia, Australia) estimates soil salinity in addition to  $\theta$ . This probe can bear up to 16 pairs of electrodes no less than 10 cm apart, and it provides an estimation of soil salinity expressed as volumetric ion content (VIC). It works at two frequencies: over 100 Mhz for  $\theta$  estimation and below 27 MHz for VIC assessment. The VIC is derived with a proprietary method and is related to  $EC_a$ , though it is not directly interchangeably with it [54]. Each TriSCAN probe is worth between 1000 and 1600 € depending on length (0.6–1.2 m).

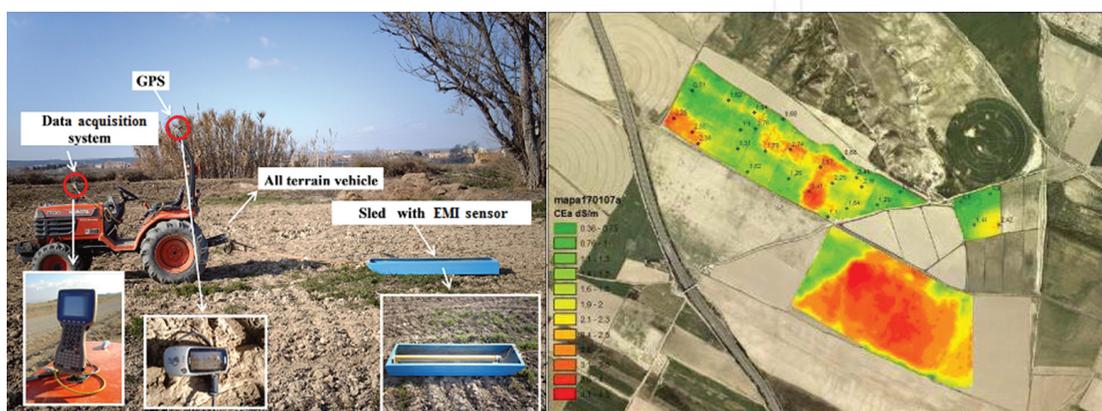
## 8. Applications of EC measurements in agriculture

The capability of EC sensors to easily and quickly take high amounts of measurements at broad spatial scales that range from profile horizons to watersheds, and at no less wide time scales that range from seconds to years, permits the development of many applications for both mapping and monitoring of soil salinity, and also soil salt dynamics. Interestingly, EC measurement systems have been used even for crop yield estimation, due to the significant correlations between  $EC_a$  and yield found for different crops such as tomato [55], corn and soybean [56–58], sorghum [57, 58], and cotton [59, 60]. The inherent integration within  $EC_a$  of various soil properties on which plant development depends, such as  $\theta$ ,  $q_b$ , clay content, and  $EC_p$ , explains such ability. The use of EC measurement systems is nowadays of paramount importance for irrigation, crop, and fertilizer management in a framework of precision agriculture (PA) in which management is adapted to the specific soil and crop characteristics as they change through space within a field, and throughout time within growing seasons.

PA is a farming management concept based on observe, measure, and thus, respond to variability in crop fields, both spatial and temporal [61]. The ultimate goal of PA is agricultural sustainability and efficiency. By matching agricultural inputs to needs, PA aims at simultaneously maximizing crop production and product quality, while minimizing environmental damage. In a PA framework, the obtaining of big data about soil properties within fields feeds the decision-making process. Provided the capabilities of the  $EC_a$  sensors described in previous sections, they are crucial to acquire this information in many applications with the eventual aim of controlling soil salinity and additionally, improving nutrition of plants avoiding harmful side effects on the environment.

### 8.1. Soil salinity mapping

$EC_a$  measurements have been widely used to characterize soil salinity at field scale. Modern mobile ER measurement systems based on a four-point array along with the use of GPS allow to elaborate 3D maps of  $EC_a$  in agricultural fields, giving rise to ER Imaging (ERI) in soil studies and agriculture [47, 62]. Good contact between the electrodes and the soil is maybe the most important constraint to have reliable  $EC_a$  measurements using ER. Depending on soil texture, water and coarse fragment contents, good contact could not be assured, and therefore, reliable measurements could neither be guaranteed with ER, overall with mobile instruments.



**Figure 4.** A mobile georeferenced electromagnetic sensor (MGES) developed for the rapid carrying out of  $EC_a^*$  surveys in agricultural plots [72].

Surveys for  $EC_a^*$  taken with EMI sensors present several advantages over surveys for  $EC_a$  with ER techniques because EMI sensors do not require any contact with the soil. Therefore,  $EC_a^*$  data can be more readily and reliably obtained on soils with stones and/or low water contents. Besides, with the specific aim of  $EC_a$  mapping, EMI techniques are usually overwhelmingly used instead of ERI, because EMI presents several advantages in addition to the previous such as i) the ability to make surveys on fields supporting growing crops, ii) the ability to make surveys on fields with beds and furrows, iii) the avoidance of soil alteration issues due to the low weight of EMI instruments, iv) the ability to survey faster because of the higher operating speeds of EMI instruments, and v) lower prices [63–65]. EMI methods present also some disadvantages, the most important of which is the more complex interpretation of  $EC_a^*$  readings regarding  $EC_a$ .

The high volumes of  $EC_a^*$  data obtained with EMI sensors are generally processed with the aid of geo-statistics [66, 67], multivariate statistics [68, 69], and GIS tools [70, 71]. EMI has been widely used for soil salinity mapping of agricultural plots, e.g. [72–75], by means of craft Mobile Georeferenced Electromagnetic Sensors (MGESs; **Figure 4**). Besides, EMI can be used along with remote sensing [76–78] to extend the capabilities of both techniques for soil salinity mapping at watershed scales.

In any case, since all  $EC_a$  measurements are affected by several other soil properties in addition to salinity, mainly water content and texture,  $EC_a$  data, and overall  $EC_a^*$  data cannot be used

alone for mapping of soil salinity. All  $EC_a$  surveys must be carried out along with traditional soil sampling and/or other sensor measurements and besides, other field observations must also be carried out.

## 8.2. Soil salinity monitoring

Since soil salinity is a dynamic property, many instruments able to automatically take  $EC_a$  measurements and additionally, to temporally save information and, to withstand the variable and tough outdoor conditions for long time spans, have been developed during the last decades. These instruments have been used mainly for agricultural water management and with increasing frequency, in a framework of PA. The  $EC_a$  technique originally used for monitoring was ER through four-point probes. Since the advent of reflectometry, however, TDR, ADR, and FDR have captured almost all monitoring applications. The only exception where ER still holds on is, maybe, the CC combined sensors, which are featured by an interesting price-quality ratio.

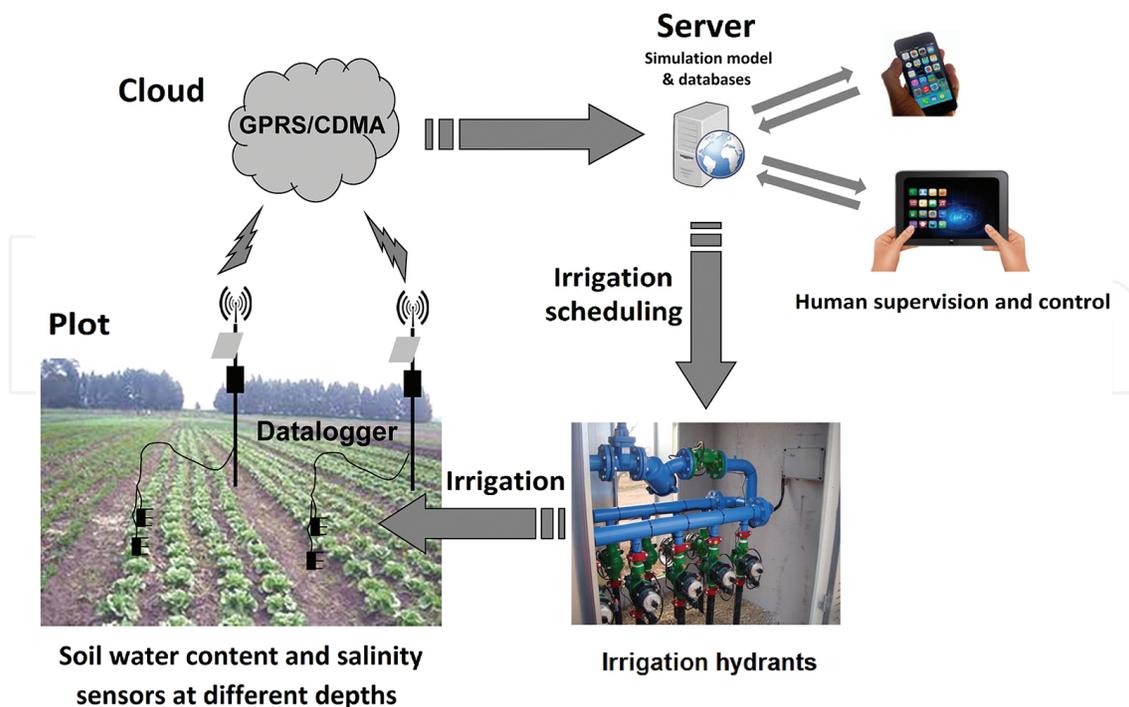
## 9. Present and future trends

The nowadays trends in  $EC_a$  sensor development are focused on improving accuracy, robustness, field installation ease, and data communication, while decreasing acquisition and maintenance expenses. All these improvements increase the applicability of  $EC_a$  sensors in agriculture, overall for irrigation and nutrient management in a PA framework. Nevertheless, while a large number of agricultural exploitations are using sensors for  $\theta$  estimation to allow the subsequent adjustment of irrigation rates, the use of  $EC_a$  sensors is far less widespread. This fact is due to issues still not satisfactorily fixed about the correct interpretation of  $EC_a$  data under the ever-changing and diverse soil conditions of agricultural fields. Although many investigations have been carried out in order to interpret  $EC_a$  and, furthermore, to assess  $EC_p$ , far more research should be performed in this regard.

More accurate  $EC_a$  interpretations and  $EC_p$  assessments, and even  $EC_{e,25}$  estimations, from sensor measurements can proceed through three ways. First, it can proceed through the development of techniques able to separate water and salinity effects on sensor responses. Second, improvement of  $EC_a$  interpretations will take place through the development of calibrations based on more reliable models for  $EC_a$ . And third, improvement of  $EC_a$  interpretations will proceed through sensor fusion, in which data from different sensors will be used together in order to ascertain soil properties and/or crop status [79]. For the first requirement, reflectometry seems to be leading. Among the three different techniques, TDR has established itself as predominant. Nevertheless, the other two reflectometry techniques (ADR and FDR) are without doubt promising. On the one hand, in ADR, water and salinity effects have been claimed to be precisely separated [80] and, on the other hand, in FDR, progress can be made through the improved interpretation of soil dielectric spectra, i.e., soil permittivity against electromagnetic frequency up to 500 MHz [37]. Along with the improvement in the separation of water and salinity effects, the development of sensors less affected by temperature should

also be performed so as to increase the robustness of measurement systems for  $EC_a$  interpretation.

Promising applications of reflectometry sensors for PA lie in the development of smart irrigation management systems (SIMS) (**Figure 5**). A SIMS has essentially two parts: i) the core, which is a decision support system (DSS) hosted in an Internet server, and ii) a field-deployed wireless sensor network (WSN), which feeds the DSS with e.g.,  $EC_a$  and  $\theta$  data. The WSN is made up of several probes distributed within the cropped field and wireless connected to one or more dataloggers which act as gateways to the WSN. The dataloggers communicate data to the Internet server by means of GSM/GPRS, 3G, or 4G, for cloud computing by the DSS. The DSS is essentially a simulation model that runs on the data from the WSN and additionally, on other data, meteorological, soil, crop, water quality, fertilization, etc., and as a consequence, produces management recommendations which are sent to the farmer in real-time. A fully automatic system would include a third part. That is an actuator network, e.g., the simplest will be for irrigation hydrant control. Such fully automated SIMS including  $EC_a$  measurements seems to have not well been developed yet. However, remote irrigation management is possible by means of systems that use field  $\theta$  sensor estimations [81, 82]. Further advances in cellular networks and cheaper and faster Internet communications will allow the spread of SIMS with fully farmer informed control through mobile telephony. This technology will benefit from the advances in  $EC_a$  data interpretation. One important way this will occur is through sensor fusion, which consists in the joint use of information originating from diverse sensors.



**Figure 5.** Scheme of a smart irrigation management system (SIMS).

Similarly to  $EC_a$ , which is an unselective factor on its own, i.e. it depends on various soil properties such as  $\theta$ ,  $Q_b$ , clay content, and  $EC_p$ , other proximal sensors as used in the field also provide unselective responses, e.g. hyperspectral, radiometric, mechanical, acoustic, pneumatic, and electrochemical [83]. Interestingly, under the concept of *sensor fusion*, all these unselective measurements including  $EC_a$  could be jointly used to generate selective information through the use of multivariate statistical methods such as MLR, PCR, and PLSR [69, 84].

Last, the use of  $EC_a$  measurements will remarkably benefit the fertilizer management for crop production in the next years. The conventional fertilizer management is generally based on monitoring the soil contents of nitrogen, phosphorous, and potassium by sampling and laboratory methods. However, since plant available N and K are in ionic form ( $NO_3^-$ ,  $NH_4^+$ , and  $K^+$ ), they contribute to  $EC_p$  and eventually  $EC_a$ . Therefore, the development of new sensors with higher capacity to separate water and salinity effects, in addition to sensor fusion, will contribute to the improvement of crop nutrition management, e.g. [85, 86]. Colburn [87] pioneering works on the secondary correlation of  $EC_a$  with soil nutrients pointed to the usage of  $EC_a$  measurements for fertilization management. However, more investigations are still needed on the application of  $EC_a$  sensors for fertilizer management [88].

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## References

- [1] Tanji, K. K. and Wallender, W. W. (2012). Nature and extent of agricultural salinity and sodicity. In W. W. Wallender and K. K. Tanji (Eds.), *Agricultural salinity assessment and management* (2nd Ed., pp. 1–25). Reston, VA: ASCE, EWRI.
- [2] Ghassemi, F., Jakeman, A. J. and Nix, H. A. (1995). *Salinisation of land and water resources: Human causes, extent, management and case studies*. Wallingford: CAB International.
- [3] Friedman, S. P. (2005). Soil properties influencing apparent electrical conductivity: A review. *Computers and Electronics in Agriculture*, 46(1–3 Spec. Iss.), 45–70.
- [4] Wolt, J. D. (1994). *Soil solution chemistry*. New York: John Wiley & Sons, Inc.

- [5] USSL Staff. (1954). *Diagnosis and improvement of saline and alkali soils* (Agriculture Handbook No. 60). Washington, DC: United States Department of Agriculture.
- [6] Maas, E. V. and Hoffman, G. J. (1977). Crop salt tolerance – current assessment. *ASCE J Irrig Drain Div*, 103(2), 115–134.
- [7] Shannon, M. C. and Grieve, C. M. (1998). Tolerance of vegetable crops to salinity. *Scientia Horticulturae*, 78(1–4), 5–38.
- [8] Rhoades, J. D. (1996). Salinity: Electrical conductivity and total dissolved solids. In D. L. Sparks, et al. (Eds.), *Methods of soil analysis part 3—Chemical methods* (pp. 417–435). Madison, WI: SSSA, ASA.
- [9] Ayers, R. S. and Westcot, D. W. (1985). *Water quality for agriculture*. Irrig drain paper 29, rev. 1. Rome: Food and Agriculture Organization of the United Nations.
- [10] Corwin, D. L. and Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture*, 46(1–3 Spec Iss.), 11–43.
- [11] Ma, R., McBratney, A., Whelan, B., Minasny, B. and Short, M. (2011). Comparing temperature correction models for soil electrical conductivity measurement. *Precision Agriculture*, 12(1), 55–66.
- [12] Johnson, P. (2007). *The design of an integrated soil moisture sensor for agriculture*. Brisbane, Queensland: Griffith University.
- [13] Groom, D. (2008). Common misconceptions about capacitively-coupled resistivity (CCR) what it is and how it works. *Environmental and Engineering Geophysical Society – 21st Symposium on the Application of Geophysics to Engineering and Environmental Problems*, pp. 36–41.
- [14] Wenner, F. (1915). A method of measuring earth resistivity. *Bulletin of the Bureau of Standards*, 12, 469–478.
- [15] Loke, M. H., Chambers, J. E., Rucker, D. F., Kuras, O. and Wilkinson, P. B. (2013). Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, 95, 135–156.
- [16] McNeill, J. D. (1980). *Electrical conductivity of soils and rocks*. Technical note TN-5. Mississauga, ON: Geonics Limited.
- [17] Saey, T., Van Meirvenne, M., De Smedt, P., Neubauer, W., Trinks, I., Verhoeven, G., et al. (2013). Integrating multi-receiver electromagnetic induction measurements into the interpretation of the soil landscape around the school of gladiators at carnuntum. *European Journal of Soil Science*, 64(5), 716–727.
- [18] Corwin, D. L., Lesch, S. M. and Lobell, D. B. (2012). Laboratory and field measurements. In W. W. Wallender and K. K. Tanji (Eds.), *Agricultural salinity assessment and*

- management (2nd Ed., pp. 265–341). Reston, VA: American Society of Civil Engineers, Environmental and Water Resources Institute.
- [19] Topp, G. C., Davis, J. L. and Annan, A. P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, 16(3), 574–582.
- [20] Savi, P., Maio, I. A. and Ferraris, S. (2011). Time-domain reflectometry (TDR) technique for the estimation of soil permittivity. In B. E. Özkaraova-Güngör (Ed.), *Principles, application and assessment in soil science* (pp. 351–370). Rijeka, Croatia: InTech.
- [21] Muñoz-Carpena, R. (2012). *Field devices for monitoring soil water content*. BUL343. Gainesville, FL: Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.
- [22] Noborio, K. (2001). Measurement of soil water content and electrical conductivity by time domain reflectometry: A review. *Computers and Electronics in Agriculture*, 31(3), 213–237.
- [23] Tarantino, A., Ridley, A. M. and Toll, D. G. (2008). Field measurement of suction, water content, and water permeability. *Geotechnical and Geological Engineering*, 26(6), 751–782.
- [24] Giese, K. and Tiemann, R. (1975). Determination of the complex permittivity from thin-sample time domain reflectometry improved analysis of the step response waveform. *Advances in Molecular Relaxation Processes*, 7(1), 45–59.
- [25] Topp, G. C., Yanuka, M., Zebchuk, W. D. and Zegelin, S. (1988). Determination of electrical conductivity using time domain reflectometry: Soil and water experiments in coaxial lines. *Water Resources Research*, 24(7), 945–952.
- [26] Muñoz-Carpena, R., Regalado, C. M., Ritter, A., Alvarez-Benedí, J. and Socorro, A. R. (2005). TDR estimation of electrical conductivity and saline solute concentration in a volcanic soil. *Geoderma*, 124(3–4), 399–413.
- [27] Nadler, A. (2005). Methodologies and the practical aspects of the bulk soil EC (sa)-soil solution EC (sw) relations.
- [28] Gaskin, G. J. and Miller, J. D. (1996). Measurement of soil water content using a simplified impedance measuring technique. *Journal of Agricultural Engineering Research*, 63(2), 153–160.
- [29] Dean, T. J. (1994). *The IH capacitance probe for measurement of soil water content*. Wallingford, UK: Institute of Hydrology, Natural Environment Research Council.
- [30] Robinson, D. A., Gardner, C. M. K., Evans, J., Cooper, J. D., Hodnett, M. G. and Bell, J. P. (1998). The dielectric calibration of capacitance probes for soil hydrology using an

- oscillation frequency response model. *Hydrology and Earth System Sciences*, 2(1), 111–120.
- [31] Seyfried, M. S. and Murdock, M. D. (2004). Measurement of soil water content with a 50-MHz soil dielectric sensor. *Soil Science Society of America Journal*, 68(2), 394–403.
- [32] He, Y., DeSutter, T., Prunty, L., Hopkins, D., Jia, X. and Wysocki, D. A. (2012). Evaluation of 1:5 soil to water extract electrical conductivity methods. *Geoderma*, 185–186, 12–17.
- [33] Rhoades, J. D., Chanduvi, F. and Lesch, S. (1999). Soil salinity assessment. Methods and interpretation of electrical conductivity measurements (FAO Irrigation and Drainage Paper 57). Rome, Italy: Food and Agricultural Organization of the United Nations.
- [34] Kelleners, T. J. and Verma, A. K. (2010). Measured and modeled dielectric properties of soils at 50 megahertz. *Soil Science Society of America Journal*, 74(3), 744–752.
- [35] Evett, S. R. (2007). Soil water and monitoring technology. In R. J. Lascano and R. E. Sojka (Eds.), *Irrigation of agricultural crops* (2nd Ed., pp. 25–84). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.
- [36] Malicki, M. A. and Walczak, R. T. (1999). Evaluating soil salinity status from bulk electrical conductivity and permittivity. *European Journal of Soil Science*, 50(3), 505–514.
- [37] Wilczek, A., Szyplowska, A., Skierucha, W., Ciesla, J., Pichler, V. and Janik, G. (2012). Determination of soil pore water salinity using an FDR sensor working at various frequencies up to 500 MHz. *Sensors (Switzerland)*, 12(8), 10890–10905.
- [38] Hilhorst, M. A. (2000). A pore water conductivity sensor. *Soil Science Society of America Journal*, 64(6), 1922–1925.
- [39] Kizito, F., Campbell, C. S., Campbell, G. S., Cobos, D. R., Teare, B. L., Carter, B., et al. (2008). Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. *Journal of Hydrology*, 352(3–4), 367–378.
- [40] Whalley, W. R. (1993). Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. *Journal of Soil Science*, 44(1), 1–9.
- [41] Visconti, F., Martínez, D., Molina, M. J., Ingelmo, F. and De Paz, J. M. (2014). A combined equation to estimate the soil pore-water electrical conductivity: Calibration with the WET and 5TE sensors. *Soil Research*, 52(5), 419–430.
- [42] Rhoades, J. D. (1981). Predicting bulk soil electrical conductivity versus saturation paste extract electrical conductivity calibrations from soil properties. *Soil Science Society of America Journal*, 45, 42–44.

- [43] Rhoades, J. D., Shouse, P. J., Alves, W. J., Manteghi, N. A. and Lesch, S. M. (1990). Determining soil salinity from soil electrical conductivity using different models and estimates. *Soil Science Society of America Journal*, 54, 46–54.
- [44] Visconti, F. and De Paz, J. M. (2012). Prediction of the soil saturated paste extract salinity from extractable ions, cation exchange capacity, and anion exclusion. *Soil Research*, 50(7), 536–550.
- [45] Rhoades, J. D. and van Schilfgaarde, J. (1976). An electrical conductivity probe for determining soil salinity. *Soil Science Society of America Journal*, 40(5), 647–651.
- [46] Jakosky, J. J. (1938). Method and apparatus for electrical exploration of the subsurface. US-Patent No. 2.138.818.
- [47] Pan, L., Adamchuk, V. I., Prasher, S., Gebbers, R., Taylor, R. S. and Dabas, M. (2014). Vertical soil profiling using a galvanic contact resistivity scanning approach. *Sensors (Switzerland)*, 14(7), 13243–13255.
- [48] Loke, M. H. (1999). Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys. Penang, Malaysia. [http://moho.ess.ucla.edu/~pdavis/ESS135\\_2013/LITERATURE/%20LokeDCREsistivity.pdf](http://moho.ess.ucla.edu/~pdavis/ESS135_2013/LITERATURE/%20LokeDCREsistivity.pdf). Accessed 13 April 2013.
- [49] Urdanoz, V. and Aragüés, R. (2012). Comparison of geonics EM38 and dualem 1S electromagnetic induction sensors for the measurement of salinity and other soil properties. *Soil Use and Management*, 28(1), 108–112.
- [50] Doolittle, J. A. and Brevik, E. C. (2014). The use of electromagnetic induction techniques in soils studies. *Geoderma*, 223–225(1), 33–45.
- [51] Dalton, F. N. and Van Genuchten, M. T. (1986). The time-domain reflectometry method for measuring soil water content and salinity. *Geoderma*, 38(1–4), 237–250.
- [52] Kelleners, T. J., Seyfried, M. S., Blonquist Jr., J. M., Bilskie, J. and Chandler, D. G. (2005). Improved interpretation of water content reflectometer measurements in soils. *Soil Science Society of America Journal*, 69(6), 1684–1690.
- [53] Evett, S. R., Schwartz, R. C., Casanova, J. J. and Heng, L. K. (2012). Soil water sensing for water balance, ET and WUE. *Agricultural Water Management*, 104, 1–9.
- [54] Buss, P., Dalton, M., Green, S., Guy, R., Roberts, C., Gatto, R., et al. (2004). Use of TriSCAN for measurement of water and salinity in the soil profile. *Engineering Salinity Solutions: 1st National Salinity Engineering Conference 2004*, Barton, ACT, pp. 206–211.
- [55] Fortes, R., Prieto, M. H., Terrón, J. M., Blanco, J., Millán, S. and Campillo, C. (2014). Using apparent electric conductivity and NDVI measurements for yield estimation of processing tomato crop. *Transactions of the ASABE*, 57(3), 827–835.

- [56] Zhu, Q., Lin, H. S. and Doolittle, J. A. (2013). Functional soil mapping for site-specific soil moisture and crop yield management. *Geoderma*, 200–201, 45–54.
- [57] Kitchen, N. R., Sudduth, K. A. and Drummond, S. T. (1999). Soil electrical conductivity as a crop productivity measure for claypan soils. *Journal of Production Agriculture*, 12(4), 607–617.
- [58] Kitchen, N. R., Drummond, S. T., Lund, E. D., Sudduth, K. A. and Buchleiter, G. W. (2003). Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. *Agronomy Journal*, 95(3), 483–495.
- [59] Corwin, D. L., Lesch, S. M., Shouse, P. J., Soppe, R. and Ayars, J. E. (2003). Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity. *Agronomy Journal*, 95(2), 352–364.
- [60] Guo, W., Maas, S. J. and Bronson, K. F. (2012). Relationship between cotton yield and soil electrical conductivity, topography, and landsat imagery. *Precision Agriculture*, 13(6), 678–692.
- [61] Vanden-Heuvel, R. M. (1996). The promise of precision agriculture. *Journal of Soil and Water Conservation*, 51(1), 38–40.
- [62] Lueck, E. and Ruehlmann, J. (2013). Resistivity mapping with GEOPHILUS ELECTRICUS—information about lateral and vertical soil heterogeneity. *Geoderma*, 199, 2–11.
- [63] Corwin, D. L. and Lesch, S. M. (2005). Characterizing soil spatial variability with apparent soil electrical conductivity: Part II. Case study. *Computers and Electronics in Agriculture*, 46(1–3 Spec. Iss.), 135–152.
- [64] Abdu, H., Robinson, D. A. and Jones, S. B. (2007). Comparing bulk soil electrical conductivity determination using the DUALEM-1S and EM38-DD electromagnetic induction instruments. *Soil Science Society of America Journal*, 71(1), 189–196.
- [65] Serrano, J., Shahidian, S. and da Silva, J. M. (2014). Spatial and temporal patterns of apparent electrical conductivity: DUALEM vs. veris sensors for monitoring soil properties. *Sensors (Switzerland)*, 14(6), 10024–10041.
- [66] De Paz, J. M., Visconti, F. and Rubio, J. L. (2011). Spatial evaluation of soil salinity using the WET sensor in the irrigated area of the segura river lowland. *Journal of Plant Nutrition and Soil Science*, 174(1), 103–112.
- [67] Ding, J. and Yu, D. (2014). Monitoring and evaluating spatial variability of soil salinity in dry and wet seasons in the werigan-kuqa oasis, china, using remote sensing and electromagnetic induction instruments. *Geoderma*, 235–236, 316–322.
- [68] Rodrigues, F. A., Bramley, R. G. V. and Gobbett, D. L. (2015). Proximal soil sensing for precision agriculture: Simultaneous use of electromagnetic induction and gamma radiometrics in contrasting soils. *Geoderma*, 243–244, 183–195.

- [69] Mouazen, A. M., Alhwaimel, S. A., Kuang, B. and Waine, T. (2014). Multiple on-line soil sensors and data fusion approach for delineation of water holding capacity zones for site specific irrigation. *Soil and Tillage Research*, 143, 95–105.
- [70] Corwin, D. L. and Lesch, S. M. (2005). Characterizing soil spatial variability with apparent soil electrical conductivity: I. Survey protocols. *Computers and Electronics in Agriculture*, 46(1–3 Spec. Iss.), 103–133.
- [71] Corwin, D. L., Lesch, S. M., Oster, J. D. and Kaffka, S. R. (2006). Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity. *Geoderma*, 131(3–4), 369–387.
- [72] Urdanoz, V., Amezketa Lizarraga, E., Clavería, I., Ochoa, V., Aragües Lafarga, R. (2008). Mobile and georeferenced electromagnetic sensors and applications for salinity assessment. *Spanish Journal of Agricultural Research*, 6(3), 469–478.
- [73] Nogués, J., Robinson, D. A. and Herrero, J. (2006). Incorporating electromagnetic induction methods into regional soil salinity survey of irrigation districts. *Soil Science Society of America Journal*, 70(6), 2075–2085.
- [74] Amezketa, E. (2006). An integrated methodology for assessing soil salinization, a precondition for land desertification. *Journal of Arid Environments*, 67(4), 594–606.
- [75] Herrero, J., Ba, A. A. and Aragües, R. (2003). Soil salinity and its distribution determined by soil sampling and electromagnetic techniques. *Soil Use and Management*, 19(2), 119–126.
- [76] Metternicht, G. I. and Zinck, J. A. (2003). Remote sensing of soil salinity: Potentials and constraints. *Remote Sensing of Environment*, 85(1), 1–20.
- [77] Yao, Y., Ding, J., Kelimu, A., Zhang, F. and Lei, L. (2013). Research on remote sensing monitoring of soil salinization based on measured hyperspectral and EM38 data. *Spectroscopy and Spectral Analysis*, 33(7), 1917–1921.
- [78] Taghizadeh-Mehrjardi, R., Minasny, B., Sarmadian, F. and Malone, B. P. (2014). Digital mapping of soil salinity in Ardakan region, central Iran. *Geoderma*, 213, 15–28.
- [79] Castrignanò, A., Landrum, C. and de Benedetto, D. (2015). Delineation of management zones in precision agriculture by integration of proximal sensing with multivariate geostatistics. examples of sensor data fusion. *Agriculturae Conspectus Scientificus*, 80(1), 39–45.
- [80] Bellingham, K. (2013). *Comprehensive Stevens Hydra Probe Users Manual. Rev. IV.* Beaverton, OR: Stevens Water Monitoring Systems, Inc.
- [81] Puerto, P., Domingo, R., Torres, R., Pérez-Pastor, A. and García-Riquelme, M. (2013). Remote management of deficit irrigation in almond trees based on maximum daily trunk shrinkage: Water relations and yield. *Agricultural Water Management*, 126, 33–45.

- [82] Navarro-Hellín, H., Torres-Sánchez, R., Soto-Valles, F., Albaladejo-Pérez, C., López-Riquelme, J. A. and Domingo-Miguel, R. (2015). A wireless sensors architecture for efficient irrigation water management. *Agricultural Water Management*, 151, 64–74.
- [83] Adamchuk, V. I., Hummel, J. W., Morgan, M. T. and Upadhyaya, S. K. (2004). On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture*, 44(1), 71–91.
- [84] De Benedetto, D., Castrignanò, A., Rinaldi, M., Ruggieri, S., Santoro, F., Figorito, B., et al. (2013). An approach for delineating homogeneous zones by using multi-sensor data. *Geoderma*, 199, 117–127.
- [85] Fuentes, S., Rogers, G., Jobling, J., Conroy, J., Camus, C., Dalton, M., et al. (2008). A soil-plant-atmosphere approach to evaluate the effect of irrigation/fertigation strategy on grapevine water and nutrient uptake, grape quality and yield. *Acta Horticulturae*, (792), 297–303
- [86] Rogers, G., Shuttleworth, L., Fox, M., Fuentes, S., Dalton, M., and Conroy, J. (2008). Evaluation of a combined soil EC and moisture sensor and its use to co-manage soil moisture and vine nitrogen in grapevines (cv. shiraz) under deficit irrigation. *Acta Horticulturae*, 792, 543–549.
- [87] Colburn, J. W. (1999). Soil doctor multi-parameter, real-time soil sensor and concurrent input control system. In P. C. Robert, R. H. Rust & W. E. Larson (Eds.), *Precision agriculture* (pp. 1011–1021). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.
- [88] Paul, W. (2002). Prospects for controlled application of water and fertiliser, based on sensing permittivity of soil. *Computers and Electronics in Agriculture*, 36(2–3), 151–163.