# The problem with “apparent electrical conductivity” in soil electromagnetic induction studies

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## Abstract

Language simplification in scientific works that use electromagnetic induction (EMI) will promote this technique in soil and water-related research and applications. One way of fostering easy understanding and communication of ideas is by omitting the usage of the term “apparent electrical conductivity” (ECa) when dealing with EMI techniques. Herein we justify that the use of ECa terminology in many EMI sensor applications is unnecessary and can create confusion due to issues on units and dimensions of ECa. While the concept of a relative electrical conductivity within a soil system may have merit, it is our opinion that the use of the term ECa is not of primary importance in many applications of EMI to the pedosphere and hydrosphere, thus, omission of the term is warranted.

**Keywords**: Electromagnetic induction (EMI); Occam’s razor; Salinity; Semantics; Soil water

**Abbreviations**: EC, electrical conductivity; ECa, apparent electrical conductivity; ECe, electrical conductivity of the saturation extract; EMI, electromagnetic induction

## 1. Introduction

Electromagnetic induction (EMI) sensors are used in many areas of sciences, such as geophysics and soil science, to understand variabilities in soil properties without direct contact to the soil (Corwin, 2008). In soil science, one particular application of EMI sensors is to assess soil salinity. Soil salinity is typically expressed as the electrical conductivity (EC) of soil-water extracts at saturation (ECe) or at some other fixed ratio of soil and water (Herrero et al., 2015). Electrical conductivity of such soil extracts measures the conduction of electricity through the solvent facilitated by the ions of the solute. Such proxies are now commonly accepted expressions of soil salinity, because they have a physical meaning: they are repeatable and can be verified by testing for errors or biases. On the other hand, ECa would be the true EC if the soil “is perfectly homogeneous and deep (regular distributed pores and substance, no heterogeneity with increasing depth)”, as stated by Heil and Schmidhalter (2019). In practice, the predicted EC cannot be validated, since field soils are not homogeneous. ECa, therefore, is a construct with an ambiguous physical meaning. It can be mentioned that the widely used —and useful— concepts of field capacity and permanent wilting percentage have fallen out of favor for the same reason. In the same way, the ECa construct is useful under the condition of avoiding its deep discussion as do most published articles achieving in this way a not complicated argumentation. This contribution aims to show that the concept of ECa is not needed in many soil studies using EMI sensors.

## 2. Soil features studied with EMI sensors

Many soil properties can be characterized by using the results from EMI surveys (Corwin et al., 2003). The reviews by Corwin and Scudiero (2019), Doolittle and Brevik (2014) or Heil and Schmidhalter (2017) provide abundant references for many targeted subsurface characteristics. Table 1 illustrates with some examples the assortment of soil–related features studied with EMI data, either alone or combined with other sensors. The sole condition is that the target feature renders an observable contrast in the electrical or magnetic properties influencing the EMI signal. For this purpose, several authors have stressed the drifting effects of the temperature of both the soil (McKenzie et al., 1989, 1997) and the EMI instrument (Robinson et al., 2004).

From a single EMI survey, several correlations can be made between the signal and different targeted features. Correlations that have been reported in many studies include the correlation of different soil features at several depths (Díaz and Herrero, 1992; Doolittle et al., 2001; Herrero et al., 2003) or with a specific soil layer only. For example, Nogués et al. (2006)

determined the correlation of the EMI signal from a single survey with salinity: (i) in the surface layer, (ii) in the subsurface layer, (iii) in both layers together, and (iv) the ECe value that was agronomically limiting. Herrero and Hudnall (2014) mapped the salinity of a specific soil surficial layer of a paddy in spite of the presence of a saline shallow water table. Ganjegunte et al. (2014) also used EMI survey to map the ECe and sodium adsorption ratio distribution in two cotton fields. Another study that dealt with correlations of EMI survey was done by Playán et al. (2008), which separately correlated signals from EMI for soils with contrasting characteristics. Correlations with remotely sensed data were performed by Rudolph et al. (2015), Casterad et al. (2018), and Nouri et al. (2018).

Recurrent soil salinity mapping is valuable for measuring the suitability of agricultural practices and environmental protection measures. An example is the use of legacy maps of salinity from irrigated areas (Castañeda et al., 2020). The use of EMI for recurrently mapping these soil characteristics is foreseeable as the EMI instruments enable researchers to overcome the effects of the localization paradox (Herrero et al., 2011) that is exacerbated by the popularity of global positioning systems (GPS) with increasing accuracy and precision. In practice, this paradox would invalidate the repeated monitoring by invasive methods along broad extensions.

## 3. To use or not to use ECa, that is the question

The physical bases of EMI responses were established in geophysics in the 19th century (Friedman, 2005) based upon the laws governing electromagnetic fields as discussed by Wait (1962). Valuable physical models of EMI responses to soil salinity have been developed, e.g., the models of the three paths of electrical conduction in unsaturated soil (Rhoades et al., 1989, 1999). Of course, these and other deterministic approaches and models (Friedman, 2005) involving ECa have been useful and necessary.

However, as far as we can determine and as can be tracked throughout the references in the above Section, many EMI studies of soil salinity have adopted a stochastic rather than a deterministic approach. Probably, the same is true for other earth features studied in the field by EMI or by other techniques relying on electrical properties of the soil. Routinely, most EMI studies have invoked apparent electrical conductivity (ECa), then it seems worth to examine its definitions.

After Spies and Eggers (1986), the reciprocal of ECa, i.e., apparent electrical resistivity, has been traditionally defined as “the resistivity of a homogeneous half-space which will produce the same response as that measured over the real earth with the same acquisition parameters (position, transmitted current, etc.)". This should include the dependence of the ECa of soils upon the frequency of the instrument (Moghadas et al., 2010).

Some other definitions of ECa found in the literature are the following:

"a complicated average of spatially distributed localized electrical conductivities in the subsurface" (Callegary et al., 2007);

*" a complex physicochemical property resulting from the interrelationship and interaction of these soil properties. [… salinity, water content, clay content and mineralogy, organic matter, bulk density, and temperature]" (Corwin, 2008);*

*"depth weighted average of the electric conductivity of a column of material to a specific depth … expressed in mS* $m^{-1}$*" (Tromp-van Meerveld and McDonnell, 2009), this definition is almost the same as the one by Greenhouse and Slaine (1983);*

*"the average EC associated with variable subsurface layers included in the EMI measurement support volume, weighted by their relative thickness and their contribution to the signal, which depends on the tool and acquisition configuration…" (Dafflon et al., 2013).*

*"… an integrated average of the electrical conductivity distribution over a certain soil volume." (Saey et al., 2015).*

*"the integrated contribution of soil physical and chemical properties and conductivity due to dissolved electrolytes in soil water and conductive minerals." (Munnaf et al., 2020).*

Clearly, these are operational definitions and provide little information about the often not fully-known mechanisms involved in the generation of the "average EC" measure. Furthermore, from the point of view of logic, why has ECa been used and not "apparent gravel content" or other similar expressions for clay, water table or petrocalcic depth, etc., when these are the target characteristics?

Specifically, the usage of ECa is unnecessary as has been shown by several studies using EMI correlations with soil salinity measurements (Lesch et al., 1992; Lesch et al., 1998; Nogués et al., 2006; López-Lozano et al., 2010; Herrero and Hudnall, 2014; Casterad et al., 2018; Filippi et al., 2018; Nouri et al., 2018), with other soil features (Campbell et al., 2015), and by modelling approaches (López-Bruna and Herrero, 1996) in which ECa was not used. The widespread unnecessary use of ECa led to this term or concept being attributed to papers in which it was not mentioned. For example, 25 out of the 51 articles not authored by us that quote the paper of Lesch et al. (1998) wrongly attribute the use of ECa to this paper. This routine use suggests that the meaning of "apparent EC" or "ECa" has evolved into an idiomatic expression perhaps with a banal use as a substitute term for the EMI signal. Examples of this is in the way McKenzie et al. (1989) explicitly used ECa as synonym of EMI reading or in the way Benavides et al. (2009) used EMI signal, EMI response, and EMI data interchangeably.

Everett (2005) discussed what EMI sensors measure. However, the nature and physical dimensions of the EMI signal are not invoked in each article involving soil features mapping. Once again, ECa seems to be often used as a superfluous term. Our argument for the present proposal is that the concept of ECa is not needed, at least when a stochastic approach is used. In these cases, one looks for the "direct" relationship between the EMI signal and the targeted soil characteristic (salinity or other). In fact, EMI readings which are a measure of the magnetic flux that results in an electromotive force moving the needle on a dial or other quantitative record such as a digital display do not reflect their true physical nature. Expressing the EMI readings as ECa, i.e., as S $m^{-1}$ or its derivatives, implies an inappropriate change in physical dimension, from electromotive force to electrical conductivity. This change should perhaps be reviewed critically by physicists or other specialists.

The EMI output can be used —and, in fact, is used under the name of ECa— as a dimensionless signal which correlation with the targeted feature is quantified by non-deterministic procedures. This is evident when correlating the EMI output of a single survey with several soil features, as in the examples provided in the second paragraph of the above section. The underlying hypothesis implying a physical dimension for ECa can be accepted or rejected, but in practice, this is an irrelevant question for many users when correlating the EMI signal against the targeted soil feature(s). In this way, the following two quotations: "Often, the use of ECa is restricted to its application as a covariate or the use of the readings in a relative sense rather than as absolute terms" by Heil and Schmidhalter (2017) when discussing the measuring of absolute values of ECa, and (ii) "[It] could be argued that it is no longer necessary to think too deeply about the cause of EMI signals" by Everett (2005), capture the essence of our proposal. In the same way Greenhouse and Slaine (1983) recommend to work in dimensionless units when displaying the data.

## 4. Prospects for the EMI sensors use

The quest for linguistic simplicity in aesthetics, philosophy, and natural sciences has persisted for centuries as shown by the widely-known William of Ockham's (1285-1347) Occam's razor as formulated by Constable et al. (1987) in their paper on electromagnetic sounding data "it is vain to do with more what can be done with fewer".

Some years ago, Korsaeth (2006) reported the commercial availability of the EM38 device in several countries. Hopefully, with future improvements in EMI technology, more kinds of EMI instruments will be designed and produced by different manufacturers, with this technology becoming increasingly popular for archeologists, consultants, farmers, engineers, environmentalists, soil mappers, and other users. It seems reasonable that most of them will embrace the use EMI sensors in the same way that scientists and other people use many laboratory or field instruments, such as conductivity and pH meters, GPS devices, etc. without explaining the physical or chemical laws governing these instruments in their reports.

For many practical users, EMI sensors are instruments that under easily determined conditions, e.g., a range of temperatures, no nearby metallic objects, plus the adjustments prescribed by the manufacturer, only deliver a signal, i.e., an EMI reading. Although a single EMI reading is ambiguous because it does not express the complex physical and chemical constitution of the soil of interest, a batch of EMI readings can provide clarity through correlations with the target measurements. Heil and Schmidhalter (2019) stated, “EM38 is useful because the readings can reflect many different soil parameters,” a conclusion that supports our considerations.

It seems highly unrealistic that the researchers in EMI applications would presume that the above types of users will need to have detailed knowledge of half space, quadrature phase magnetic field component, Maxwell’s equations, or similar concepts pertaining to the foundations of EMI methods. In fact, the mention of ECa in many soil prospection reports is accompanied with poor –often because unnecessary– discussion about the physics behind the method. The EMI signals can be designated with specific abbreviations for each kind of field reading, e.g., EMh and EMv for horizontal and vertical position of the coils, respectively, when the EMI sensor has parallel coplanar coils, or with similar adequate letters/subscripts for perpendicular coils or other configurations in multi-receiver sensors, or for different elevations of the sensor above-ground, etc.

## 5. Final remarks

Most of the articles cited by Doolittle and Brevik (2014) and Heil and Schmidhalter (2017) use the term ECa or similar, even if their approach is stochastic. On the other hand, we have not found in the literature any misgivings in the use of ECa. Both ECa and apparent resistivity have long been used, with no difficulties, in diverse research and application domains. Our concern treated in this Note is a semantic one, or —perhaps more exactly— an urge to use for each concept a distinctive word even if it differs from the traditional or routine term. In this way, as science is not based upon consensus or upon opinion polls, we advocate that the mention of ECa or apparent electrical conductivity is often unnecessary for correlating the EMI signal with the target's magnitude and for its subsequent mapping. Avoiding its use is an application of Occam's razor. As Gracián (1647) stated in his Aphorism no. 105, "The good, if short, is doubly good".

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**Table 1** Some examples of soil-related features studied using EMI sensors either alone or combined with other sensors

| **Characteristics studied** | **References** |
|---|---|
| Archeological and civil structures | de Smedt et al., 2013; Saey et al., 2013 |
| Available water content | Hezarjaribi and Sourell, 2007 |
| Buried metal objects | Nelson and McDonald, 2001; de Smet et al., 2012 |
| Crop growth | Stadler et al., 2015 |
| Crude oil contamination | Cassiani et al., 2014 |
| Depth to argillic horizon | Sudduth et al., 2010; Xue et al., 2020 |
| Different features for delineation of management zones | Morari et al., 2009; López-Lozano et al., 2010; Dennerley et al., 2018 |
| ECe, exchangeable Ca, exchangeable Mg, and cation exchange capacity | McBride et al., 1990 |
| Exchangeable Ca and Mg | Li et al., 2019 |
| Olive trees trunk growth | Aragüés et al., 2005 |
| Organic matter | García-Tomillo et al., 2017; Huang et al., 2017 |
| Potato tubers | Farooque et al., 2020 |
| Shoreline structure | Weymer et al., 2018 |
| Site-specific seeding | Munnaf et al., 2020 |
| Soil depth and pasture | Bork et al., 1998; Serrano et al., 2010 |
| Soil organic carbon | Jaynes, 1996 |
| Soil taxa delineation | Ammons et al., 2015 |
| Soil water content | Sheets and Hendrickx, 1995; Martínez et al., 2018 |
| Soil water dynamics | Huang et al., 2018 |
| Tridimensional distribution of soil salinity | Von Hebel et al., 2014; Zare et al., 2015 |
| Vineyard terroir study | Priori et al., 2019 |