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ELECTRICAL GEOPHYSICAL METHODS IN AGRICULTURE

Larisa Golovko^{1,2}, Anatoly I. Pozdnyakov^{3,4}

¹ Landviser, LLC, 828 Davis Rd., League City, TX 77573, USA

² RiceTec, Inc., P.O. Box 1305, Alvin, TX 77512, USA

³ Moscow State University, Faculty of Soil Science, Dept. of Physics and Melioration, Moscow 119899, RUSSIA

⁴ Central Peat/Bog Research St. – Dmitrov Branch of Russian Inst. of Reclaimed Lands, Dmitrov 141832, RUSSIA

info@landviser.com

antpozd@bk.ru

ABSTRACT

Conventional methods of electrical geophysics, i.e. vertical electrical sounding, four-electrode probe, non-contact electromagnetic profiling, and self-potential were modified for shallow agricultural and environmental studies. The methods have been applied in Russia for soil research the last forty years. In a last decade methods of electrical conductivity (EC) became increasingly popular in USA and worldwide to assist in precision agriculture practices. Several on-the-go soil EC sensors were developed and successfully applied. Our group together with Landviser, LLC has developed two portative geophysical devices, LandMapper ERM-01 and ERM-02 measuring electrical conductivity, resistivity and potential and suitable for mapping agricultural production fields as well as small agronomy research plots. The devices can also be used in lysimeters, greenhouses and on soil samples in laboratory. Compared with conventional methods of soil analysis, the electrical geophysical methods allowed evaluating groundwater table, salt content, depth and thickness of soil horizons, polluted or disturbed layers in soil profiles, and stone content with an estimation error <10%. The methods provide extensive data on spatial and temporal variations in soil electrical properties, which relate to the distributions of other essential soil properties. The electrical properties were incorporated with the data from conventional soil analyses via geostatistical methods to enhance the estimation of a number of soil physical and chemical properties and to assist soil survey. This paper presents brief introduction into the soil electrophysics and demonstrates various applications of the modified geophysical methods in soil physics, soil genesis, precision agriculture, and environmental engineering.

Key words: geophysics, electrical resistivity, electrical conductivity, soil survey, precision agriculture

INTRODUCTION

Soil properties are of high importance in many human activities, such as agriculture, forestry, landscaping, environmental protection, recreation, and civil engineering. Soil survey for different applications requires quick and, when possible, non-disturbing estimations of numerous

soil properties, such as salinity, texture, stone content, groundwater depth, and horizon sequences in soil profiles. Many of these properties are highly spatially variable yet some are also temporally unstable. An accurate evaluation of soil properties is complicated by the nature of their variability; however, conducting soil measurements with a high sampling density is costly and time-consuming.

Conventional methods of soil analysis for precision agriculture mapping mostly require disturbing soil, removing soil samples, and analyzing them in a laboratory. It has been noted that, if soil samples are collected with the intensiveness appropriate for meaningful precision agriculture management, the sampling costs would exceed any potential benefits from the site-specific approach [1].

Electrical geophysical methods, however, allow rapid measurement of soil electrical properties, such as electrical conductivity, resistivity, and potential, directly from soil surface to any depth without soil disturbance. The in-situ methods of electrical conductivity (e.g. four-electrode probe and electromagnetic induction) were routinely used to evaluate soil salinity [2-4]. Some electrical geophysical methods were used to map groundwater tables and salinity [5, 6], preferential water flow paths, and perched water locations [7]; to outline locations of landfills [8]; and to evaluate water content [9], temperature [10], texture [11], and structure [12] of soils.

Despite the advantages of electrical geophysical methods, their applications to soil science problems are not straightforward and require thorough study. The methods are not commonly applied in soil studies mainly due to three reasons. First, the theory about nature of development and distribution of soil electrical fields, whose parameters are measured with the electrical geophysical methods, was not fully developed [13-16]. Second, the equipment for geophysical methods of vertical electrical sounding, four-electrode profiling, ground-penetrating radar, etc. manufactured and readily available in the USA is suited only for exploration of deep geological profiles. Therefore, the distributions of electrical properties in shallow (0-5 m) soil profiles usually can not be measured with such equipment. The methods need to be modified for soil investigations. Finally, the in-situ measurements of electrical parameters need a specific calibration in every study to be reliable to monitor and map different soil properties. Relationships between electrical properties and other soil chemical and physical properties are very complex because many soil

properties may simultaneously influence in-situ measured electrical parameters [11, 17].

Nowadays only the methodologies of four-electrode probe and electromagnetic induction method for application on saline soils are well developed [18-20]. The electrical properties of other soils have remained unstudied until the last decade when specifically modified for soil studies electrical conductivity sensors became widely available [21]. Soil EC is of particular interest for agricultural management for several reasons.

First, newly developed technologies (Veris, Inc., Geonics, Ltd., Landviser, LLC, etc.) allow obtaining fast, dense, and accurate GIS-compatible soil EC or ER measurements [22].

Second, soil EC is related to several soil properties important for plant growth [23-26], including: soil salinity; level of soil compaction; depth to clay pan or groundwater; gravel layers or lenses, sand, silt, and clay contents; soil drainage; total soil organic matter content; NPK contents; soil pH, cation exchange capacity, etc.

Third, modern technologies usually can measure ER in subsoil at a range of depths essential for plant growth (<http://www.landviser.com/prod01.htm>). This feature adds to the unique importance of soil EC or ER for site-specific management, because neither digital elevation models nor remote sensing can assess the subsurface soil properties. Generally the EC equipment measures a bulk electrical conductivity or resistivity in a relatively large volume of soil (on average 0.5 m³) removing the bias of “point” soil sampling by augers, etc. and can better characterize mid-scale (within field) soil variability, which is the most important factor in the delineation of management zones for precision agriculture practices.

Finally, on-the-go EC sensors measure soil electrical conductivity non-destructively *in-situ* providing a more accurate assessment of the real conditions in soil, which makes them particularly suitable for soil monitoring and time-series statistical studies of the anthropogenic changes in cultivated soils ([27]b).

Although geophysical methods of electrical conductivity mapping both via direct current method of four-electrode probe (Veris Technologies) and via electromagnetic induction (Geonics EM31 and EM38) are now state-of-the-art technologies in precision agriculture, the magnitude of EC studies are empirical correlative field studies. Unfortunately, majority of research in this area is not unified and lacks underlying theory about laws of soil electrophysics governing the nature of soil electrical conductivity. This paper presents an attempt to summarize the current research in soil electrophysics [13, 14, 16].

To address the discussed problems, the objectives of this paper are: (i) to overview the basic law of electrophysics govern the electromagnetic fields in solutions, porous media and soils; (ii) to discuss principles of electrical geophysical methods for measuring various

electrical properties and to demonstrate their relationships with other soil physical and chemical properties; (iii) to evaluate the influence of soil-forming processes on distributions of electrical properties in soil profiles; (iv) to present case applications of the modified electrical geophysical methods of EC mapping, vertical electrical sounding, and self-potential to agricultural research.

METHODOLOGY

1. THEORY

1.1 History of electrical geophysical methods

The first attempt to measure electrical resistivity of soils was made at the end of the nineteenth century with the two-electrode technique. Whitney et al. [28], Gardner [29], and Briggs [10] developed relationships between soil electrical resistivity and soil water content, temperature, and salt content. The two-electrode method measures the sum of both soil resistivity and the contact resistivity between the electrode and soil. The latter is very erratic and unpredictable.

Simultaneously researchers in deep geophysical exploration continued experimenting with electrode arrangements and different applications. The earliest record – patent #17844 was issued to Frank S. Chapman “Method for Detecting Presence and Approximate Location of Metallic Masses”; no date given. Through the 1880’s, 90’s and into the twentieth century, numerous others filed patents on similar systems. Conrad Schlumberger was issued patent #1,163,469 on December 7, 1915 for his “Method of location of ores in the subsoil and 14 years later another patent (#1,719,786) on July 2, 1929 for his “Method for location of Oil-Bearing Formation.”

Wenner [30] based on the work of Schlumberger suggested that a linear array of four equally spaced electrodes would minimize soil-electrode contact problems if potential-measuring and current-induced electrodes are separated in space. Since then all the electrical resistivity methods applied in geophysics and soil science are still based on the standard **four-electrode principle**.

Method of four-electrode probe has been used in soil practices since 1931 for evaluating soil water content and salinity under field conditions [9, 31, 32]. Halvorson and Rhoades [2] applied a four-electrode probe in the Wenner configuration to locate saline seeps on croplands in USA and Canada. Austin and Rhoades [33] developed and introduced a compact four-electrode salinity sensor into routine agricultural practices. A special soil salinity probe, which utilized the same four-electrode principle, was also designed for bore-hole measurements and/or for permanent installations in soils for infiltration and salinity monitoring [34, 35]. An electrical cell used to measure electrical conductivity of soil samples, pastes, and suspensions, was also developed based on four-electrode

principle [36]. The advantages of electrical conductivity measurements for evaluation of soil salinity led to development of soil salinity classifications using electrical conductivities of soil pastes and suspensions [37]. Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed [4, 38]. The method of four-electrode probe was also used for evaluation of some other soil properties, such as soil water content [9, 39]; structure [12]; bulk density, porosity, and texture [11]; stone content and pollution by oil-mining facilities [16], locations of the burial places in archaeology and criminology [40] 1997; [41], etc. Recently measurements of soil electrical resistivity were coupled with geostatistical methods to develop accurate soil maps [41, 42].

1.2 Modern technologies

Thus, the method of measuring electrical resistivity or conductivity using four-electrode probe has been applied in geology and soil science for almost a century and the theory of the method is well developed. It should be noted that Schlumberger, Sundberg, Wenner and many others were participants in the early development of electrical methods. Electrical methods increased in popularity, sophistication and sensitivity as technology improved. Modern deep geophysical devices measure several other electrical parameters of the subsurface and have automatic commutation of the different electrode combinations (SYSKAL, IRIS, ABEM LUND System). It is customary to calculate induced polarization (IP) and metal conductivity factor (MCF) using data collected in both time domain and frequency domain.

Using data collected from different four-electrode combinations, a resistivity/IP pseudosection of the subsurface is produced. 2D inversion software is used to create a two dimensional view of real geometry. Combining 2D views gives a 3D view of areas having contrasting electrical properties. The recent advancement in deep geophysics were in developing inversion software (GEOTOMO Software, <http://www.landviser.com/softwaregallery.htm>)

Methods of electrical exploration have been used to find formation faults, formation bedding, water saturated aquifers, mineral deposits, and hydrocarbons including coal. Vertical electrical sounding and geoelectrical imaging methods work well in applications having good resistivity contrast.

Recently, electrical geophysical methods become increasingly popular in soil and environment studies. The methods have been adapted to soil studies through hardware modification (smaller electrodes, array spacing, low-capacity batteries) which increased devices portability. This modification was essential since depth of interest for

soil investigations is much smaller than for geological exploration. Besides, soils usually have lower contrast in electrical parameters between horizons. Usually, many factors simultaneously influence electrical parameters measured in soils in-situ.

Methods of field soil electrophysics include direct current (DC) and auxiliary current (AC) methods. Parameters of stationary electrical fields are measured by contact (DC) methods. Predominantly in soil studies, electrical conductivity or resistivity is measured by DC methods of four-electrode probe such as EC-mapping and vertical electrical sounding (VES) (Veris Technologies, Inc; Landmapper ERM-01 by Landviser, LLC). However, natural electrical potentials exist in soils between soil horizons, between soils and plants, and in a direction of predominant water and solution transport. Method of self-potential can be used to outline water fluxes. Currently, the only soil-adapted equipment on the market capable of measuring natural electrical potentials in soils and plants is Landmapper ERM-02 by Landviser, LLC.

Parameters of non-stationary (electromagnetic) fields are measured by non-contact (AC) methods, which measure parameters of secondary electrical fields induced in soils and do not require physical contact with soil (EM-devices by Geonics, Ltd, PulseEKKO 1000 Ground Penetrating Radar (GPR)). These AC methods are fast on-the-go non-destructive devices, but they measure EC somewhat less accurately than DC contact methods and also are severely depth-limited especially on conductive clay, saline and nutrient-rich soils. Time-domain reflectometry (TDR) technique has been evolved into fast and reliable method of measuring soil water content using contact high-frequency AC current [43-45]. Advances in TDR technology have brought cost of such devices to the affordable range and they can be used to map and monitor soil water content in topsoil of agricultural fields (Dynamax Theta Probe) [46, 47].

Laboratory and lysimeter soil electrophysics utilizes TDR water-sensors and small EC four-electrode probes to study water and solution transport [48-50], soil water properties [51], colloid and aggregate formation [52] and soil-plant energetic balance [53].

Still EC-mapping is a predominant electrical geophysical technique widely used in agriculture. All of the field EC-sensing methods have different advantages and limitations.

Methods of EM cannot directly measure different resistivities or conductivities of soil horizons and provide only average or bulk electrical conductivity of the soil profile [54]. Besides, not a single modification of EM method can evaluate soil layers shallower than 0.5 m. GPR evaluates profile differentiation of soil electrical conductivity in shallow subsurface soils, but its performance is often poor in electrically conductive environments, such as salty and clay soils [55]. NRCS has

published Ground-Penetrating Radar Soil Suitability Maps derived from the soil attribute data contained in the State Soil Geographic (STATSGO) and the Soil Survey Geographic (SSURGO) databases (<http://soils.usda.gov/survey/geography/maps/GPR/index.html>) for whole continental USA.

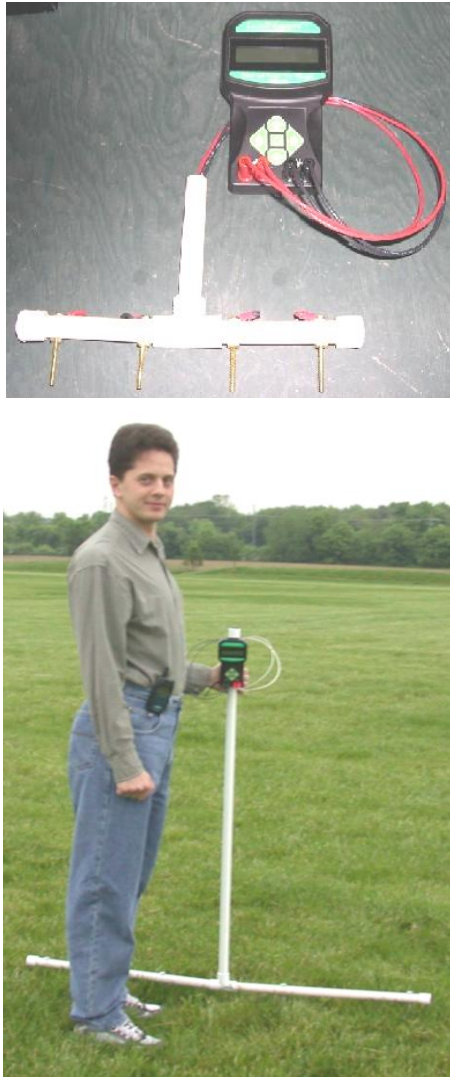


Fig. 1. Landmapper ERM-01 device. (a) Landmapper with a soil pit probe, (b) typical setting for soil mapping application.

Although EM-31 and EM-38 devices of Geonics are virtually non-destructive and potentially can be applied on perennial crops, the electromagnetic techniques provide low depth resolution and generally cannot measure EC in the top soil layer shallower than 0.5 m. Besides, both technologies are quite expensive, which limits their adoption on small and mid-sized farms.

DC electrical geophysical methods, such as electrical profiling (EP) and vertical electrical sounding (VES), implied in Veris' and Landviser' instruments, are more accurate and applicable over a wide range of electrical conductivities and can be easily scaled down to measure differences in electrical parameters on a smaller scale, i.e. between soil horizons in the vadose zone. However, the Veris's device is bulky and measurements are semi-destructive, i.e. cannot be conducted during plant growth and/or on perennial horticultural crops.

A new digital device, Landmapper ERM-01, was developed by Landviser LLC to be used within a broad range of agricultural applications (Fig. 1). This device is portable, fast, accurate, compact, safe, and affordable. It uses fully customized, interchangeable, and easily constructed four-electrode probes, which make it highly versatile for many applications, ranging from ER measurements in the laboratory and soil pits to non-destructive field mapping of soil layers at 0-15 ft depth. Thus, the new Landmapper ERM-01 can be a valuable tool for fast and economical soil mapping and response monitoring in precision agriculture [46].

1.3 Theory of electrical resistivity

Direct current EC methods utilize well-known four-electrode principle to measure electrical resistivity or conductivity, as shown in the Figure 2. Thus, LandMapper ERM-01 measures potential difference ($\Delta\phi$), which arises between two electrodes (M and N), when electrical current (I) is applied to other two electrodes (A and B).

In theory, electrical resistivity (ER) of a material is defined as follows:

$$ER = \frac{A\Delta\phi}{LI} \quad (1)$$

where L is the length of a uniform conductor with a cross-sectional area A . A/L is a geometrical coefficient (K), which is easily calculated for different in-situ electrode arrangements and laboratory conductivity cells.

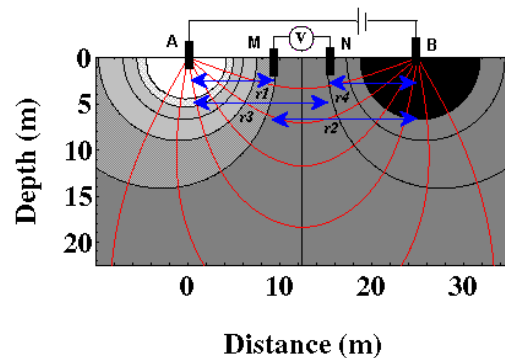


Fig. 2 Illustration of typical four-electrode array used in EC-mapping

LandMapper ERM-01 calculates electrical resistivity using formula:

$$ER = K \frac{\Delta\phi}{I} \quad (2)$$

The direct digital output of the device is electrical resistivity in Ohm m. Those can be converted into electrical conductivity (S/m) by using reciprocal of the measured resistivity:

$$EC = \frac{1}{ER} \quad (3)$$

Thus, the measured results may as well be presented in convenient for US soil scientists form of soil electrical conductivity (EC).

Coefficient K in Eq.2 is geometrical factor depending on the distances among the electrodes AMNB. The vast majority of the 4-electrode arrangements (arrays) employed in geological and soil exploration is linear central-symmetric arrays similar to one shown in Fig. 2. In such arrays the potential-measuring MN electrodes are placed between A and B electrodes and AM=NB. The coefficient K for such arrays is calculated with formula:

$$K = \pi \frac{[AM] \cdot [AN]}{[MN]} \quad (4)$$

where [AM], [AN], and [MN] are respective distances between electrodes measured in meters.

The depth of the measurement depends on the electrical resistivity of the soil as well as on the geometry on the four-electrode probe. For the probes in Wenner configuration (equally spaced, central symmetric, [AM]=[MN]=[NB]=*a*), which are supplied with the LandMapper ERM-01, the depth of the investigation is approximately equal to electrode spacing (*a*) for most soils [56]. K coefficient for Wenner arrays is calculated as:

$$K = 2\pi a \quad (5)$$

LandMapper ERM-01 is typically supplied with one four-electrode probe in Wenner configuration and coefficient K (K1) preset in the device memory. LandMapper ERM-01 can only be used with central-symmetric electrode arrays and cells; thus was used in Ec-mapping with probes in Wenner configuration and in soil vertical electrical sounding with arrays in modified Schlumberger configuration. Landmapper ERM-02 can utilize any possible electrode arrangements; thus can be used for dipole-dipole arrays and in addition has capability to measure natural electrical potentials in soils and plants (<http://www.landviser.com/prod03.html>).

Thus, various modern electrical geophysical methods technologies can be used in agriculture to measure soil electrical properties, which are the parameters of natural and artificially created electrical fields in soils. To explain the measured electrical parameters and develop correlation models between electrical and other soil properties we

have developed the theory of mobile electrical charges in soils [13].

1.4. Theory of mobile electrical charges in soils

Formation and distribution of natural and artificial electrical fields in various media, including soils, is a result of variability in electrical charge densities in these media. It was shown that regardless of the considered scale and the nature of electrical charges in soils, basic laws of electromagnetism, i.e. Maxwell, Poisson, and Boltzmann laws, are applicable to describe formation and distribution of electrical fields in soils [16].

Soil properties influencing the density of mobile electrical charges were found to be exponentially related with electrical resistivity and potential based on Boltzmann's law of statistical thermodynamics. Relationships were developed between electrical properties and other soil physical and chemical properties, such as texture, stone content, bulk density, water content, cation exchange capacity, salinity, humus content, and base saturation measured in-situ and in soil samples [14, 53].

1.4.1. EC and ER versus soil physical and chemical properties

By merging electromagnetic theories with pedogenesis we can identify the soil properties directly or indirectly related to the soil electrical conductivity [14, 16]. In particular, soil properties influencing the density of mobile electrical charges were found to be exponentially related to electrical resistivity and potential based on Boltzmann's law of statistical thermodynamics. Soil electrical charge is determined by an ion exchange, which in turn depends on three factors:

- Isomorphic substitutions in clay minerals [57, 58];
- Breakage of ionic bonds in organo-mineral complexes [59];
- and alteration of charge distribution in macromolecules of soil organic matter.

Therefore, soil chemical properties, such as humus content, base saturation, cation exchange capacity (CEC), soil mineral composition, and the amount of soluble salts, are related to the total amount of available charges in soils. Soil physical properties, such as water content and temperature, influence the mobility of electrical charges in soils. From our study of electrical resistivity vs. soil water content relationships in laboratory conditions, the mobility of electrical charges exponentially increases with an increase in water content [16, 51]. Other soil physical properties, such as soil structure, texture, and bulk density, alter the distribution of mobile electrical charges in soils.

Considering the qualitative structure of CEC, soils can be broadly subdivided into two groups. The first group is soils with CEC filled by Ca^{+2} , Mg^{+2} , Al^{+3} , and H^{+} . These

soils are formed by the processes of podzolization, lessivage, eluviation-illuviation, humification, mineralization, and gleization in humid areas [60]. Spodosols, Alfisols, Gelisols, Histosols, Ultisols, and Mollisols can be considered as soils of the first group. The processes of calcification, salinization, alkanization, pedoturbation, humification, and mineralization in arid and semiarid areas form the second group of soils with CEC filled by Ca^{+2} , Mg^{+2} , and Na^{+} . Soils of the second group are represented by Aridosols, Vertisols, and some Mollisols.

1.4.1.1. Arid regions

In salt-affected soils of arid regions concentration of soluble salts influences ER values the most. Various studies have shown that 70% of EC variations can be explained by concentrations of soluble salts [61, 62]. Hence, EC and ER were used successfully for predicting and mapping soil salinity in such regions [18, 42, 63].

Spatial variability in the EC/soil salinity relationship on a field scale also has been well addressed. Application of advanced statistical techniques, such as kriging, cokriging, multiple regression with spatially uncorrelated residuals from the regression model created opportunities for even better mapping of soil salinity based on EC measurements [42, 63]. For example, a combination of extensive EC-sensing data with soil salinity data in cokriging allowed a substantial reduction in the number of samples required to accurately assess soil salinity [42]. EC measurements also have been used to characterize properties of the vadose zone in arid aquifers.

The relationship between EC and soil salinity is complicated by other factors influencing field EC measurements, such as soil texture, water content, and bulk density [17]. Thus, in situ measurements of electrical conductivity require field/site calibration for suitable monitoring and mapping of soil salinity. The proposed calibration approach provides a solid background for soil salinity prediction, based on EC measurements.

1.4.1.2. Humid regions

Application of EC measurements in humid regions, however, has been hindered by the complex nature of the relationship between EC and soil properties affecting it in soils with low concentration of dissolved electrolytes. Moreover, certain soil properties can be dominant in the EC/soil model under specific soil conditions.

Soil texture, moisture and cation exchange capacity (CEC) are among the soil properties of the highest influence on EC. [64] found that soil moisture was better correlated with EC (r^2 from 0.77 to 0.88) than clay content (r^2 from 0.25 to 0.49) in several soils from Ontario, Canada. Banton et al. [11], Sudduth et al. [26] also

observed significant correlation for soil EC with clay content and CEC. Soil temperature, water content and depth to clay pan were found to be among the main influences on soil EC by Sudduth et al. [21]. In Missouri soils with a dense clay pan layer Sudduth et al. [21] found that EC used in exponential and polynomial regression models was an excellent predictive tool for depth to clay pan layer. Kravchenko et al. [24] observed that field measurements of soil EC along with field topography were significant variables in predicting soil drainage classes via discriminant analysis in typical Illinois soils.

Some of the influences on soil EC may not be of an immediate interest to EC data users, moreover, they may be considered as noise effects that actually diminish usefulness of EC data. Effects of temperature and soil moisture are the most evident of such influences. However, they can be eliminated or reduced to being negligible by careful planning. For example, the minimal influence on EC observed when EC measurements are collected from different fields, when the air temperatures are in the same range, will eliminate the temperature effect.

Based on both theoretical considerations and lab experimental observations it has been shown that soil moisture has little to no effect on soil EC variations at soil water contents close to field capacity [14, 51, 65]. Field studies reported in the literature also support the idea that the effect of water content on soil EC can be eliminated by appropriate timing of EC measurements. However, although the idea is theoretically sound and supported by lab measurements and indirect field observations, so far there are insufficient data to quantify correlations between soil water content and EC at different moisture levels in the field.

It is important to realize that even when some of the influences on soil EC (i.e., temperature or moisture) are minimized, soil EC in humid regions will still be related to more than one soil parameter (i.e. clay content and CEC). Hence, calibration will always remain an inevitable part of using EC data.

CASE STUDIES

Despite numerous EC-mapping case studies conducted in many countries by numerous researchers, only a few studies demonstrated a complex approach to electrical geophysical site survey. In most studies only one technique of EC-mapping, either EM or four-electrode method was employed. We have developed a complex methodology of ER-mapping and vertical electrical sounding to aid in agro-reclamation mapping [14, 66, 67]. This approach was tested in humid areas near Moscow [68] and arid areas near Astrakhan [69]. In specific situations when study requested outlining the subsurface fluxes, the technique of self-potential was employed in addition to methods of electrical resistivity [70].

1.1. Electrical geophysical methods for agricultural soil mapping

In the situations when one or two soil properties highly influences measured electrical properties, EC methods can be used for evaluation of such properties *in-situ*. Our recent results have shown good correlations with various soil properties including but not limited to pH, resistance to penetration, soil water content, and stone content. The technology can be used to enhance existing data from soil series maps using the measured electrical resistivity maps.

The applications of the methods included studying soil texture, compaction, and soil morphology; mapping soil spatial variability within agricultural fields, catenas, or landscapes; locating genetic horizons, hardpans, compacted or disturbed layers, stones, and groundwater tables in soil profiles; and monitoring soil drying or soil solution transport. Our previous research has shown that ER measurements can also be used to outline soil salinity and stone content, to detect and map impermeable layers, and to monitor water and fertilizer states in soil.

1.1.1. Electrical resistivity vs. stone content

The resistivity of rocks or stones is much higher (about 10^4 - 10^{12} ohm m) than the resistivity of soil horizons with any texture. Therefore, high electrical resistivity will indicate the presence of stones in soil profiles of any type and geographical region.

We developed a rough scale for evaluation of stone content in Crimea soils, Ukraine. Note, that these values may be different for other soils/regions (Table 1).

Table 1. Typical values of ER of stony fine-textured soils of Crimea, Ukraine.

Stone content by volume	Electrical resistivity
— % —	— ohm m —
<5	<50
5-20	50-80
20-40	80-120
40-60	120-150
60-80	150-250
>80 (slightly eroded rocks)	>250 (1000-3000)

During the study and collaboration with scientists from Nikitskii Arboretum, Yalta and Crimea Institution of Irrigated Orchards, Eupatoria, three soil properties were found to be essential for estimation of soil potential productivity for usage under orchards. These properties are stone content in the layers of 0-50 cm, 50-100 cm, and >100 cm; the depth to impermeable rock; and the depth of the A-horizon. We developed a practical guideline for estimation of soil productivity from the stone content and

depth to the rock for some typical fruit trees, which can be viewed at <http://www.landviser.com/stone.htm>.

To increase the efficacy of the mapping of soil suitability for orchards, the extent of mapping of an area can be conducted on selected characteristic distances AB/2 equal to 90, 180, and 360 cm with four-electrode probe. In addition data from the Crimea region of Russia showed a good correlation between electrical resistivity and stone content in soils. Recommendations on the usage of stony soils under orchards were developed from that data. A study was conducted on skeletal soils (Paleoxerolls and Lithic Xerorthents) formed on carbonate-cemented marine deposit, limestone, or pebbles of alluvial origin in the western part of Crimea Peninsula, Ukraine. The stone content varied from 2 to 90% of fragments coarser than 2 mm by volume and stony layers occurred in soil profiles at depths as shallow as 12 cm [46].

1.1.2. Electrical resistivity vs. soil texture and resistance to penetration

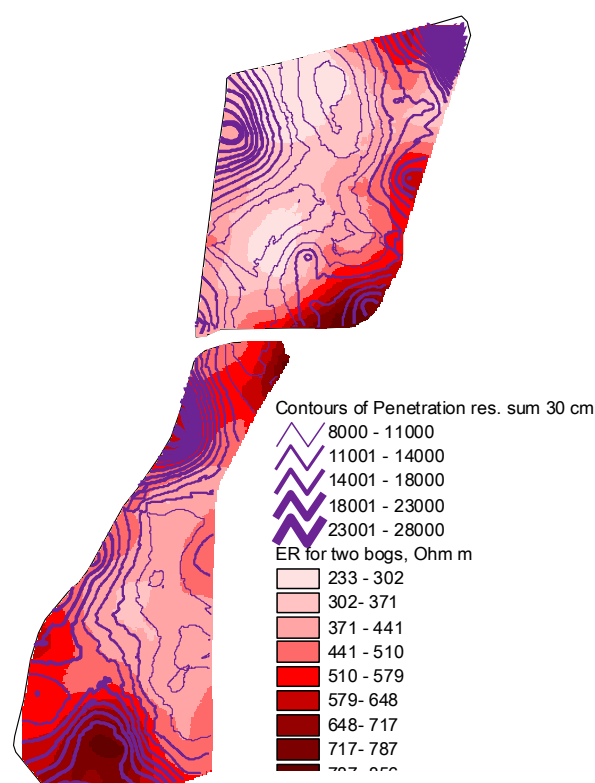


Fig. 3. Corresponding electrical resistivity and resistance of penetration maps for Berryland soil series in New Jersey, USA.

The soil resistance to penetration was measured with the Rimik Cone Penetrometer on two renovated cranberry bogs located on Berryland soil series. The electrical resistivity was measured at the same locations (~200) with

the Wenner probe (Landmapper ERM-01) effective to 30 cm depth. The sum of the resistance to penetration to 30 cm depth and electrical resistivity map have shown very similar patterns (Fig. 3). Low ER and mechanical resistances indicated presence in top soil of some soft clay and silt material, which was confirmed by subsequent excavations. The study is published in [46].

1.1.3. Electrical resistivity to monitor salt solution transport

As salt concentrations and water content are two major factors influencing electrical properties of soils in arid regions, numerous studies were conducted to map soil salinity using EC methods [42], but relatively few studies applied methods of electrical imaging to study the profile distributions of salts and water content in native arid soils [15, 69, 71]. Method of vertical electrical sounding can be used to study various processes in soil such as freezing-melting, wetting-drying and solution transport in soils [16, 72]. The measurements can be conducted repeatedly during the process by the electrodes installed on the soil surface without any disturbance. 2D visualization of the resistivity cross-section can be done with RES2DINV software.

We conducted controlled experiment of extremely saline solution infiltration in arid sandy soils with high groundwater table in Astrakhan area of Russia. The experiment is a model of technological disaster at a gas-oil refinery, but results are promising for studying lower saline solutions, i.e. fertilizer applications in agriculture [73].

Figure 4 shows horizontal slices of the electrical resistivity and water content in the saline solution infiltration experiment. During the experiment the highly concentrated (94% NaCl) solution applied to the 0.3 m² frame in three doses, 20 cm, 50 cm, and 100 cm. After complete infiltration ER was measured with VES methods, then soil samples were extracted with auger at the grid at the infiltration front and below. The next day the soil pit was dug at the infiltration frame to observe horizontal variability of the saline solution and ER was measured at 5 cm grid with four-electrode probe and Landmapper ERM01 and soil samples were collected at the same grid. The control measurements were conducted on native soils nearby without saline solution application. The native sandy soils were extremely dry at the surface and had ER=1000-2000 Ohm m. Resistivity decreases with depth and reaches 200-300 Ohm m at 1.5 m. The groundwater is shallow in the area (1.7 m). However, in saline infiltration experiment resistivity is considerably lower (60-80 Ohm m) starting with 0.6 m. In 20 cm solution case the low ER=1 Ohm m layer reached 25-28 cm, but after 6 hours by VES interpretation saline solution was at 80 cm, which was verified by soil pit observations (after 24 hours

solution was at 100 cm). In 50 cm solution the saline layer was detected by VES at 80 cm immediately after infiltration and was detected at 120-130 cm at 24 hours. Immediately after infiltration of 100 cm saline solution VES detected that solution reached groundwater fringe, by augering after 6 hours detected 7 cm dry layer between water fringe and solution front, but that layer was also saline (Fig. 4).

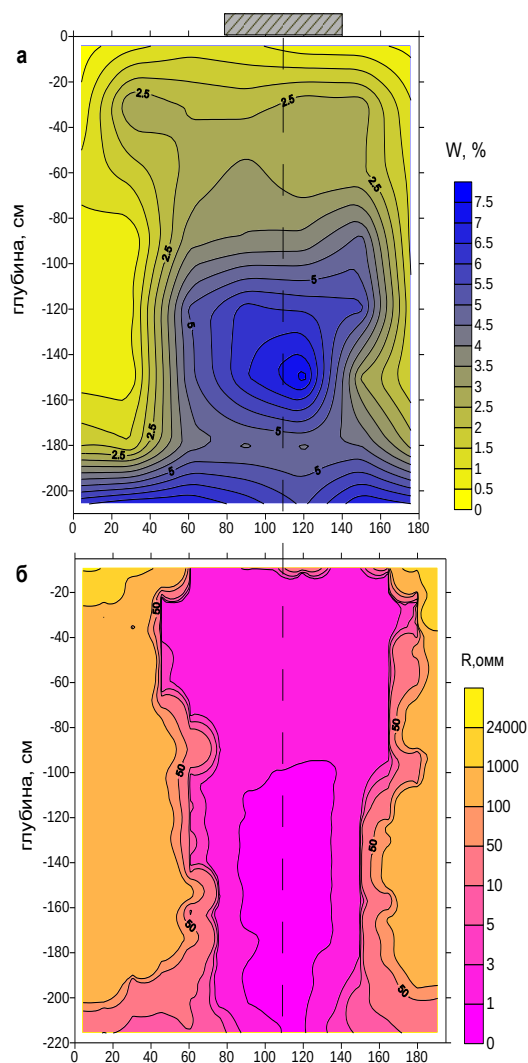


Fig. 4. 2D image of the soil water content (auger sampling) and electrical resistivity (VES) at 6 hours after infiltration of 100 cm extremely saline solution in sandy soil.

1.1.4. Electrical resistivity to outline and clarify soil series maps

The study was conducted to clarify small scale soil maps (SSURGO) in southern New Jersey, USA [46]. The developed maps of soil electrical resistivity generally followed the pre-existing maps of soil series for the

research areas, but revealed significantly more variability within the soil map units. In some cases the data from the electrical resistivity survey were in better agreement with the remote sensed imagery, which revealed cranberry stress due to water logging conditions than with the existing soil series maps for the area.

The results of ER mapping on blueberry farms indicated general correspondence of the spatial patterns in soil properties to the SSURGO delineated soil maps for the area. Thus, the soils of Atsion series have the highest ER (up to 10,000 Ohm m), which decreases in a row of Atsion-Berryland-Hammonton-Mullica series. The electrical resistivity for the same soil series may be quite different for different farms, but always helped to distinguish between soil series within a field.

1.2. EC for predicting crop yields

There is growing evidence that soil EC can be used for characterizing soil productivity and for predicting crop yields. For example, Johnson et al. [23] separated the studied fields in Central Colorado into several classes based on magnitude of EC values. They observed that soil physical and chemical properties, including, bulk density, clay content, soil organic matter content, and biological soil properties, including microbial biomass C and N, and mineralizable N, as well as surface residue mass, were significantly different among the soil EC classes. Kravchenko [24] applied joint multifractal analysis to evaluate spatial aspects of the relationship between corn and soybean grain yields, field EC measurements and topography in an experimental field in Central Illinois. Analysis indicated that the relationship between crop yields and EC differed across the landscape. Variations in EC were shown to be a particularly good predictor of soybean grain yield distributions on higher terrain, i.e. hill tops and shoulders, where EC was successfully used to identify poorly drained areas unfavorable for plant growth.

Kravchenko [24] noted that the strength of the relationship between EC and crop yields in humid regions might be affected by amount of precipitation obtained during growing season. Observed dependency of the crop yield/EC relationship on amounts of precipitation strengthens the need for a compound approach to EC applications for agricultural management in non-arid regions. It is clear that all the factors involved in EC/crop yield correlations, namely, (i) precipitation and (ii) its subsequent horizontal and vertical redistribution determined by field topography, landscape position and hydraulic soil properties, need to be identified. Their contribution to the observed relationships needs to be understood and quantified for EC to become a useful component of agricultural management as a yield predictor.

We tested various techniques to characterize spatial variability of soil properties within a test cranberry bed [70]. Soil and crop analysis were conducted in 1999 and 2000 for samples collected from 216 locations within 6.7 acres cranberry bed planted on Atsion soil in 1993 following removal of blueberries. Data show high variability in topsoil pH (3.8-5.0), water content (0.01-0.62 cm³ cm⁻³), infiltration rate (0.05-4.3 cm/min), water-soluble Fe (0.1-13.0 mg/L), and electrical resistivity (124-1,653 Ω m) as well as in yield (0-3,384 berries/sq.m), vine density, berry quality, and PRR (0-95% of roots infested). An in-situ soil moisture sensor (DYNAMAX soil water probe) was used to measure water content at the soil surface (0-5 cm) over the same 216 locations several times during the growing season. Although soil water content changes significantly between precipitation and irrigation events, some areas within the bed tend to experience extreme wetness or dryness, indicating non-uniform drainage in the bed.

As was shown [51], the soil water content demonstrated some correlation (exponential or power relationships) with measured electrical resistivity for soils of humid areas (NJ). The presence in topsoil materials with higher water holding capacity, such as clay and silt, and especially water logging conditions can significantly increase the mobility of electrical charges and decrease ER. Those complex conditions are stressful to most crops.

Soil conditions, favorable to PRR, such as soil water logging, higher pH and soluble iron [74] are indicators of reduced environment in soil and all are stressful to plants [75]. As a general outline of soil Red/Ox potential [76], low soil electrical resistivity indicates problem areas on cranberry bed, which correspond to low yield.

1.3. Electrical geophysical methods to study plant-soil systems

The previous section demonstrated that complex of soil properties influencing plant growth and yield can be identified and mapped with electrical geophysical methods. Moreover, our recent studies have shown that soil electrical potentials influence plant growth directly and electrical geophysical methods can be used to monitor plant health [77]. The biopotentials or micro electrical potentials of the plant tissues and their effect on plant growth have been studied by plant physiologists for some time. However, practically no research has been conducted on natural electrical potentials between soil and a growing plant, or “macropotentials” of the plants.

Earth is an “electrical” planet in nature. All the processes in biosphere occur in ever-changing electrical fields, which arise due to changes in solar activity, magnetic field of earth, and electrical processes in atmosphere. These global and local fluctuations in electrical fields create electro-tropism at all levels of

biosphere, including the Soil-Plant system. Electro-tropism in Soil-Plant system is a combination of the natural electrical potential differences on the interfaces inside soil (between soil horizons or peds), on the interfaces inside growing plant (between different plant tissues), as well as between soil and plant. The largest electrical potential differences were observed inside soils. The natural electrical potentials (stationary and fluctuating) in soils were studied by our group for last 40 years and the results were summarized and presented on 17th World Congress of Soil Science in 2002 [13].

Recently, we advanced to the measurements and research of the natural electrical potentials between soil and growing plants [78]. Natural electrical potentials between soils of major genetic types and more than 100 species of native and cultural plants of Ukraine, Russia, and Philippines in different growing conditions have been studied in 2003-2005 [53].

We used LandMapper ERM-02 (Fig. 5) and our patented non-polarizing electrodes made from standard AgCl-electrodes cupped with solidified agar solution of 1% KCl [79]. The reference electrode was always placed in the topsoil near a growing plant and the measuring electrode was firmly contacted to the surface of the tissues of the plant (flowers, stems, or leaves).



Fig. 5 Measurement of electrical potential between soil and banana plant in Philippines using Landmapper ERM-02.

The electrical potential difference between soil and a plant is always negative. This difference is highest during spring and for young plants in summer, and decreases in fall when plants in Russia are ready for dormancy. Tropical plants showed higher potential differences than plants of temperate climate. The potentials for all plants decreased in a row flower-leaf-stem. Electrical potential of herbaceous plants is directly related with the leaf area, the highest potentials were observed for burdock, cow-parsnip, and young banana palms. The research is underway for

establishing relationships between natural electrical potentials/resistivity of plants/soils and plant's water stress [80].

CONCLUSIONS

The electrical parameters were related with soil properties influencing the density of mobile electrical charges in soils by exponential relationships based on Boltzmann's distribution law of statistical thermodynamics.

The electrical properties of soils can be easily measured with geophysical methods *in situ* and in laboratory conditions and provide information about densities of mobile electrical charges in soils on different levels of soil organization ranging from core sample to landscape scales. Soil electrical properties reflect the transport of substances in landscapes, geochemical connection, and formation of soil climatic and topographic sequences. Mobile electrical charges concentrate in subordinated soils of landscapes.

Our research team studied the relationships between electrical properties and other commonly considered soil properties for over forty years and evaluated the applications of various electrical geophysical methods for quick in-situ soil characterization for agricultural and environmental applications.

The case studies revealed significant correlation of the electrical resistivity, measured in-situ with many soil properties, mainly soil water content, pH, resistance to penetration, texture, and stone content. The difference in complex soil properties distinguishing various soil series in humid areas are reflected in measured electrical resistivity. Application of LandMapper ERM-01 in routine soil survey can help to speed up soil mapping fine-tune the existing spatial soil databases.

The within-field variation in soil properties causes the variation in crop yields, revealing the stable patterns in crop loss, especially on perennial horticultural crops. As an indicator of the complex of soil properties influencing yield, electrical resistivity was found correlated with crop yields.

Electrical potentials between topsoil and growing plants can be used to monitor plant growth and health continuously and non-destructively.

With the advantages of quickly obtaining extensive data on the vertical and lateral distributions of electrical properties in soil profiles without soil disturbance and possibility of measuring parameters of growing plants in natural conditions electrical geophysical methods should be utilized in precision agriculture and soil/plant research more often. Future research can bring up more interesting applications.

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