ELECTRO-GEOPHYSICAL METHODS FOR SOIL SURVEY OF AGRICULTURAL LANDS

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Abstract

Geophysical methods measuring electrical conductivity (EC) and resistivity (ER) are important for soil survey and can provide information about soil subsurface quickly and non-destructively, with minimal sampling, and in the range of depths. Compared with electromagnetic methods and ground penetrating radar, methods of EC/ER measured with direct current and four-electrode probe have fewer limitations and were successfully applied on clayish and saline soils as well as on highly resistive Alfisols and Spodosols. The complex approach to agronomic electrical soil mapping is outlined below: vertical electrical sounding (VES) of major soils on the territory of survey; electrical mapping territory with 2-5 four-electrode probes sensing specific key depths selected after VES interpretation; preparing electrical survey maps in GIS; selecting key soil pits on the territory of survey based on electrical maps; measuring electrical parameters on the walls of soil pits; collecting soil samples from the layers with contrasting electrical parameters; measuring electrical parameters and conventional chemical/physical properties in soil samples and developing relationships between soil properties and electrical parameters; interpolating field soil survey using laboratory tests and pedotransfer functions. The final detail soil map obtained with electro-geophysical methods was compared with classical soil map and economical advantage of this approach was evaluated.

Introduction

Accurate information about soil properties is required 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. 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 (Swinton and Lowenberg-DeBoer, 1998).

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 (Halvolson and Rhoades, 1976; Chang et al., 1983; Rhoades et al., 1989). Some electrical geophysical methods were used to map groundwater tables and salinity (Arcone et al, 1998), preferential water flow paths, and perched water locations (Freeland et al., 1997); to outline locations of landfills (Barker, 1990); and to evaluate water content (Edlefsen and Anderson; 1941), temperature (Briggs, 1899), texture (Banton et al., 1997), and structure (Nadler, 1991) 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 (Pozdnyakov and Pozdnyakova, 2002; Pozdnyakov, 2001; Pozdnyakov et al., 1996). 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, mapping of the distributions of electrical properties in shallow (0-5 m) soil profiles usually is not convenient with such equipment. The methods and equipment 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.

Nowadays the methodologies of four-electrode probe and electromagnetic induction method for application on saline soils are well developed (Rhoades et al., 1990; Hendrickx, et al., 1992; Mankin et al., 1997). 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 (Sudduth et al., 2001). 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 (Kitchen et al., 1999).

Second, soil EC is related to several soil properties important for plant growth (Johnson et al., 2001; Kravchenko et al., 2002; Sudduth et al., 2000), 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.

Finally, modern technologies usually can measure ER in subsoil at a range of depths essential for plant growth. 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 m^3) 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.

The objectives of this paper are: (i) to discuss principles of electrical geophysical methods for measuring various electrical properties and to demonstrate their relationships with other soil physical and chemical properties; (ii) to outline methodology for mapping horizontal and vertical variability in farmed fields; (iii) to present case applications utilizing complex approach and modified electrical geophysical methods of EC mapping and vertical electrical sounding to agricultural research.

Methodology and Theory

EC-mapping is a predominant electrical geophysical technique widely used in agriculture. EC methods differ in techniques by which they evoke electrical potential difference in soil. DC methods inject DC current via four-electrode probes inserted into soil. Methods of EM induction evoke secondary electrical current in soil through electromagnetic induction.

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 (Richards et al., 1956). Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed (Nadler, 1982).

The method of four-electrode probe was also used for evaluation of some other soil properties, such as soil water content; structure; bulk density, porosity, and texture; stone content and pollution by oil-mining facilities, locations of the burial places in archaeology and criminology (Butler and Llopis, 1997), etc. Recently measurements of soil electrical resistivity were coupled with geostatistical methods to develop accurate soil maps (Butler and Llopis, 1997; Pozdnyakova and Zhang, 1999).

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 (Pozdnyakov, 2001). 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 (Perrot, 1977; Sparks, 1997);
- Breakage of ionic bonds in organo-mineral complexes (Moshi et al., 1974);
- 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 (Pozdnyakov et al., 2006). 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 (Wilding et al., 1983). 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.

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 (Williams and Hoey, 1987). Hence, EC and ER were used successfully for predicting and mapping soil salinity in such regions (Williams and Baker, 1982).

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 (Lesch et al., 1992). 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 (Pozdnyakova and Zhang, 1999). 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. 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.

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. Kachanoski et al. (1992) 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. (1997), Sudduth et al. (2000) 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. (2001). In Missouri soils with a dense clay pan layer Sudduth et al. (2001) found that EC used in exponential and polynomial regression models was an excellent predictive tool for depth to clay pan layer. Kravchenko et al. (2002) 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. 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 Study

Despite numerous EC-mapping case studies conducted in many countries, 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 (Kokoreva et al., 2007):

1. Study available soil maps and landscape of the survey area and select locations for a few complete vertical electrical soundings (VES down to 5-10 m).
2. VES of major soils on the territory of survey.
3. Electrical mapping of the territory with 2-5 four-electrode probes sensing specific key depths selected after VES interpretation.
4. Preparation of electrical survey maps in GIS.
5. Selection of key soil pits on the territory of survey based on electrical maps and measurement of electrical parameters on the walls of soil pits. Collection of soil samples from the layers with contrasting electrical parameters.
6. Measurements of electrical parameters and soil chemical/physical properties of samples in laboratory.
7. Transformation and interpretation of field soil survey with the support of laboratory tests and pedotransfer functions.

All the proposed measurements of soil electrical parameters both in the field and laboratory can be carried out with only one hand-held device LandMapper ERM-02 developed and distributed by Landviser, LLC (USA-Russia). Landmapper is very versatile device for soil mapping and monitoring and allows soil surveying down to 10-m depth without (or with minimal) excavation (Pozdnyakova et al., 2004).

This 7-step approach is illustrated below in a case mapping project of intensively cultivated potato field near Moscow. Figure 1 shows locations of VES and points for EC mapping (steps 1-3).

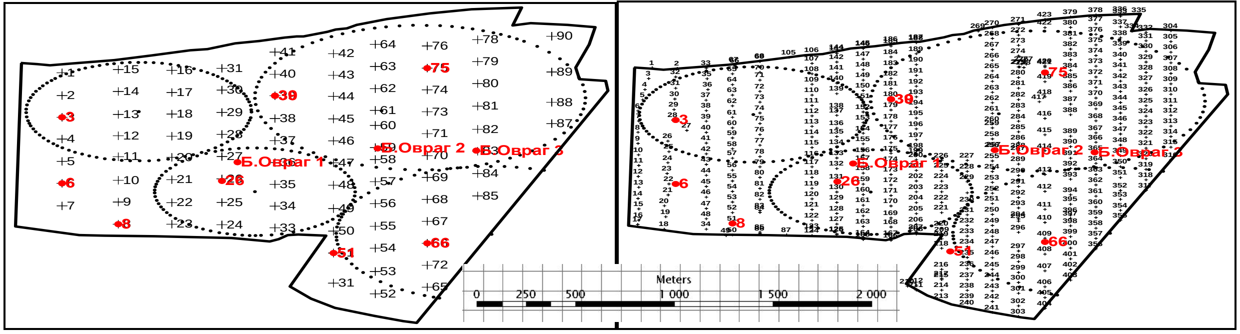


Figure 1: Locations of 11 soil pits (in red), 90 VES (b) and 423 multi-depth EC mapping locations (b).

Maps of electrical resistivity at four layers were prepared with Surfer and ArcMap software (Fig. 2) in step 4. Next, 10 soil pits were dug out on the survey field as illustrated by red dots on Figures 1 and 2.

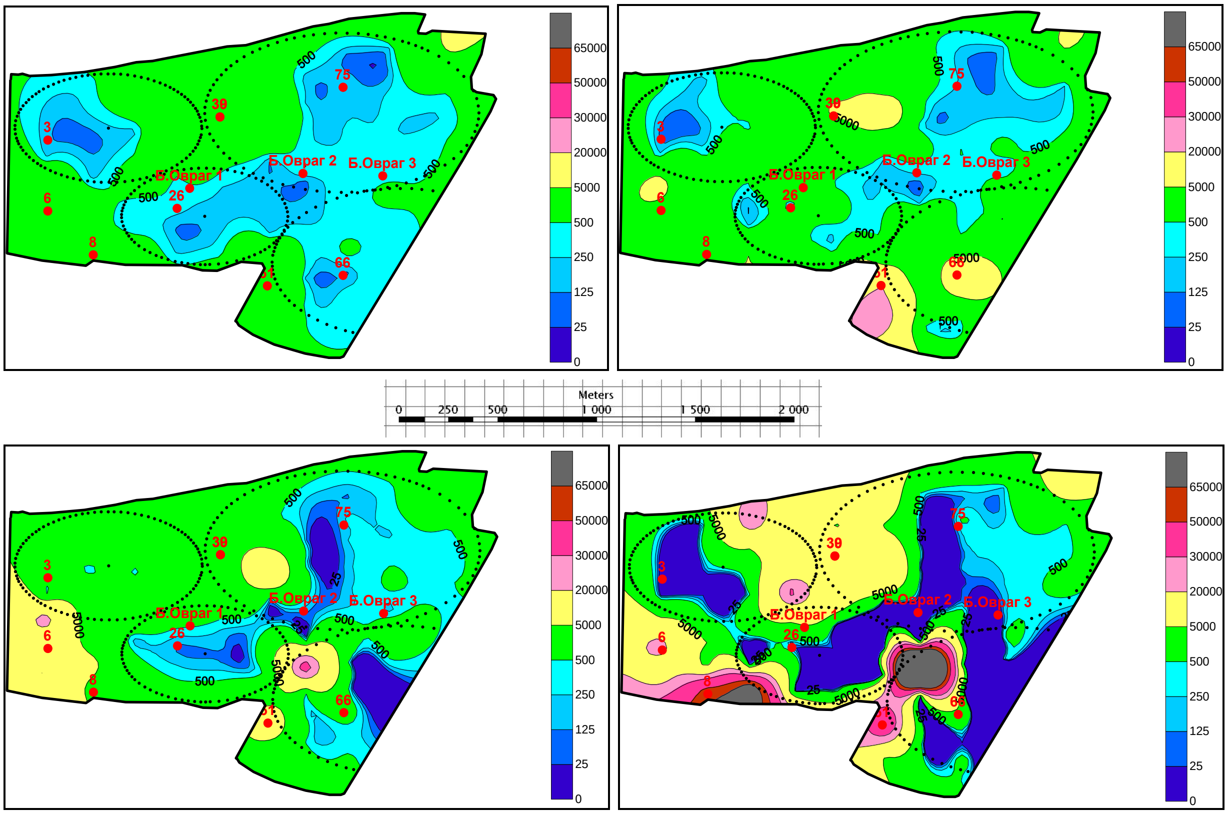
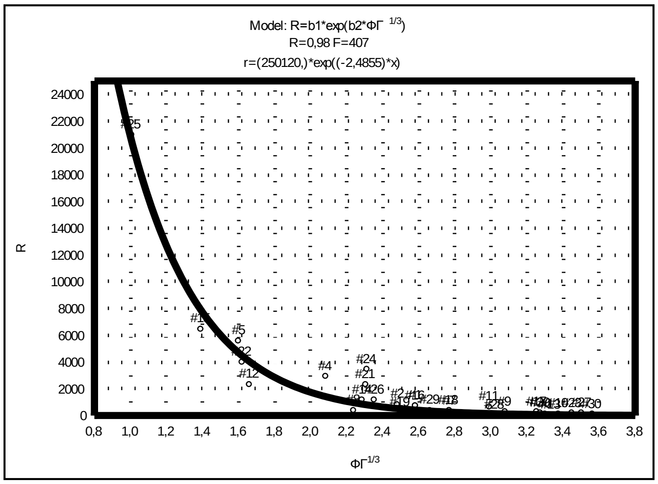


Figure 2: Maps of electrical resistivity (ER) at 10 cm (a); 30 cm (b); 60 cm (c); and 480 cm depths.



Electrical resistivity and other soil properties were measured in soil samples collected from characteristic soil horizons in step 5. Exponential relationships between ER and clay content, filtration coefficient, field capacity and field soil moisture were obtained in step 6 (Fig. 3).

Figure 3: Exponential relationship between field ER and clay content of soil samples from different soil horizons.

Finally, using obtained exponential relationships, the field ER maps were transformed into maps of soil physical properties in step 7. Figure 4 shows maps of clay content, filtration coefficient, field capacity for 480 cm depth. Result of the study was map of redistribution of water and nutrients within the field, which was used by farmer as an aid for site-specific fertilizer applications.

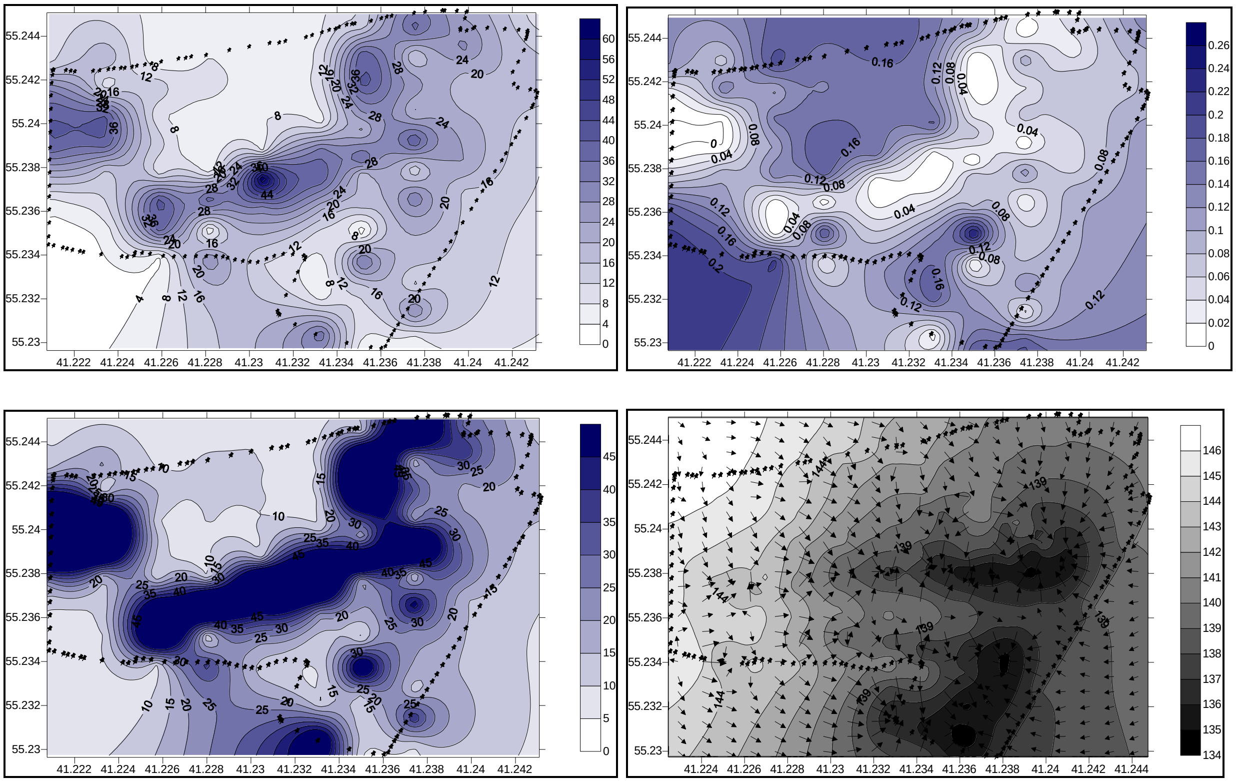


Figure 4: Maps of soil physical properties at 480 cm depth created with non-destructive geophysical ER mapping: clay content map (a); filtration coefficient map (b); map of field capacity (c); map of redistribution of water and nutrients in landscape (d).

Conclusions

The electrical parameters are 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 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.

The case studies revealed significant correlation of the electrical resistivity, measured in-situ with soil physical properties, mainly soil water content, texture, field capacity and filtration coefficient. The difference in complex soil properties distinguishing various soil series in humid areas are reflected in measured electrical resistivity. Application of LandMapper ERM-02 in routine soil survey can help to speed up soil mapping fine-tune the existing spatial soil databases.

With the advantages of quickly obtaining extensive data on the vertical and lateral distribution of electrical properties in soil profiles without soil disturbance electrical geophysical methods should be utilized in precision agriculture and hydrological studies more often.

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