Soil Electrical Conductivity

Conductivity is a measure of the ability of a material to transmit (conduct) an electrical charge. It is an intrinsic property of the material, just like other material properties such as density or porosity. The usefulness of soil conductivity stems from the fact that sands have low conductivity, silts have a medium conductivity, clays have a high conductivity, and saline soils are the most conductive (Fig. 1). Consequently, conductivity (measured at low frequencies) correlates strongly to soil grain size and texture (Williams and Hoey, 1987). Clays are more conductive partly because they hold more moisture and also because they have greater surface area, which provides more particle-to-particle contact than coarser soils.

When there is a significant amount of dissolved salts in the soil, either in the pore water, or in a water film surrounding the soil particle, EC levels increase (Rhoades and Corwin, 1990).

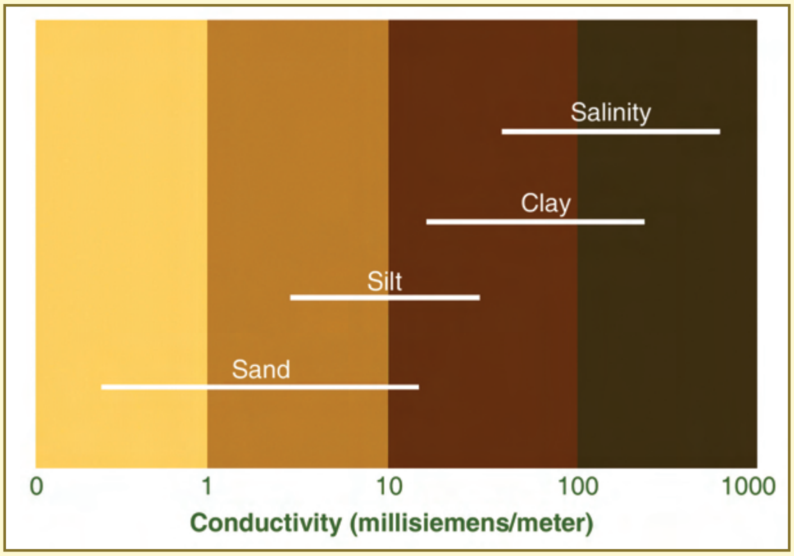

Fig. 1. Soil electrical conductivity depends on soil grain size and salinity.

Summary

Soil properties often vary significantly within a field, and one of the challenges in precision agriculture is collecting enough soil data to accurately delineate this. Soil electrical conductivity (EC) has become a widely used tool for mapping soil variability within fields. Soil EC measurements are typically correlated with soil texture, moisture, and salinity. Soil texture is an important factor in crop yields because it relates to water-holding capacity, cation-exchange capacity, rooting depths, drainage, and other properties that impact crop production. Although high salinity is an issue in only a small percentage of U.S. soils, in those areas it can have a pronounced effect on crop yields. Soil EC maps are being used in various site-specific management approaches, including variable plant populations, zone sampling, and as a component of variable nutrient management.

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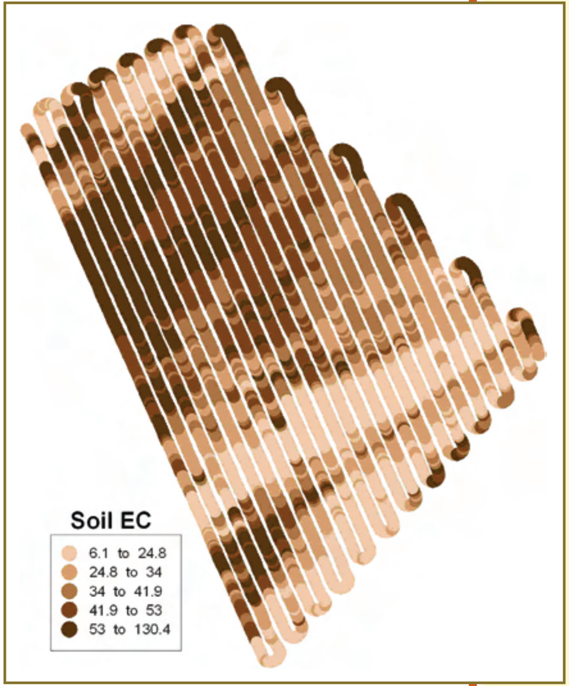
Soil EC is expressed in millisiemens (mS) or decisiemens (dS), as siemens are the preferred conductance unit of measurement. The inverse of soil conductivity is soil resistivity, and those measurements are expressed in ohms (Ω). Conductivity and resistivity are sides of the same coin—if soil is high in conductance, it will be low in resistance. These measurements are not to be confused with other soil measurements that use similar terms, such as hydraulic conductivity (the ability of soil to conduct or transmit water), or soil mechanical resistance, a property typically measured with a soil penetrometer.

Another possible source of confusion is the difference between a soil EC value reported on a soil test analysis from a lab and soil EC values generated from field measurements. Laboratory analyses for soil EC are used for salt classification and use a saturated paste extract or solution. These tests use a uniform moisture content to remove any conductive effect caused by soil texture, and thus any clay–moisture interactions are eliminated. Field EC, sometimes called bulk soil EC or apparent soil EC, is largely dependent on differences in texture. Typically, the only case when lab EC and field EC are correlated is when soil salinity is high enough to be the primary driver of the field EC measurements. While lab EC values are used to assess salinity, field EC measurements have a variety of uses, including soil sample site selection. Our discussion here will focus on field-measured soil EC values.

Fig. 2. Example of raw (unprocessed) EC data from a Mississippi field.



Field EC Measurements

Typically, soil EC is collected with a mobilized unit and a GPS, which results in a dense data set of 80 or more EC values per acre (Fig. 2). These maps can then be used by consultants and growers in a variety of precision agriculture approaches, such as creating management zones, setting sample locations for laboratory analysis, creating variable rate prescriptions, and yield analysis.

There are several aspects of EC mapping that distinguish it from other soil mapping efforts, such as grid sampling and soil surveys.

- **Density**—the high number of data-points per acre is only feasible with on-the-go sensing and can generate maps that don't rely on interpolation to delineate zones. In Fig. 2, the soil pattern, or spatial structure, is visibly apparent.

- Electrical conductivity **maps relate primarily to physical properties** of the soil, as well as chemical properties. Consequently, it is not a replacement for chemical analysis. This will be covered in greater detail below.
- Electrical conductivity arrays penetrate deeper than the equipment physically operates. This allows **delineation of subsurface properties**.
- Because the main soil property (soil texture) that EC relates to is relatively permanent, EC mapping represents a **long-term investment** (Fig. 3). While absolute EC values vary with moisture content (and soil temperature and bulk density), the patterns delineated are consistent. Exceptions are fields that have significant earth moving, or have changes in salinity.

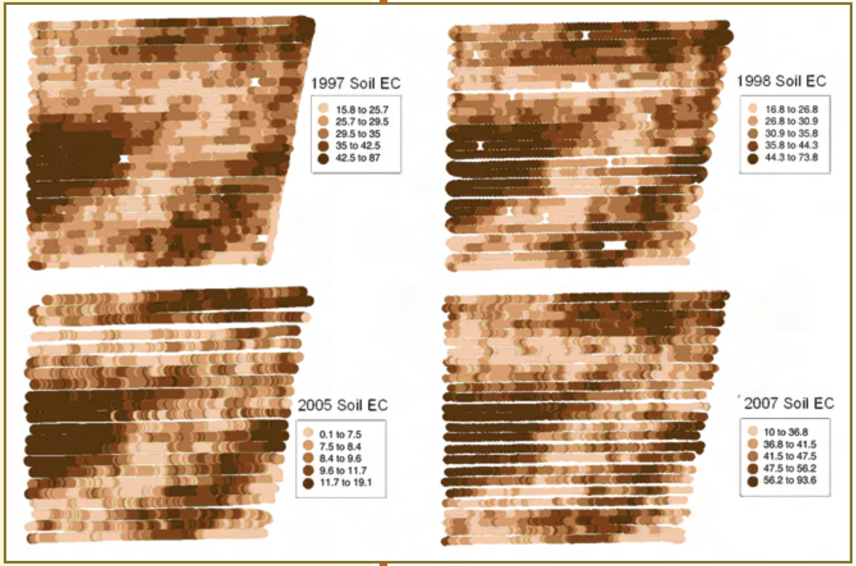


Fig. 3. Repeated EC mapping reveals similar soil patterns.

The two primary methods of measuring soil conductivity are by direct contact or electromagnetic induction (EMI). Direct contact methods use at least four electrodes that are in physical contact with the soil to inject a current and measure the voltage that results (Fig. 4A). On the other hand, EMI does not make contact but instead uses a transmitter coil to induce a field into the soil and a receiver coil to measure the response (Fig. 4B). The advantages of direct contact methods are robust construction, freedom from metal interference, and that there is no need for daily calibration. These advantages are why direct contact methods have been accepted for widespread use in commercial agriculture. The portability and non-invasive characteristics of the EMI method make it advantageous for some research applications.

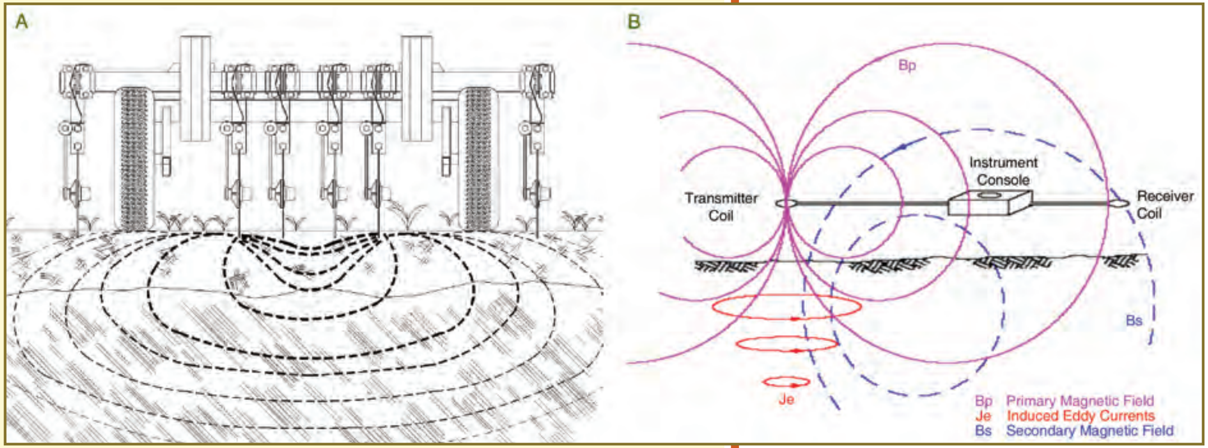


Fig. 4. (A) Direct-contact soil conductivity systems inject current directly into the soil. (B) EMI method induces a field into the soil and a receiver coil measures the response.

Fig. 5. Veris Technologies 3100 model (direct contact).

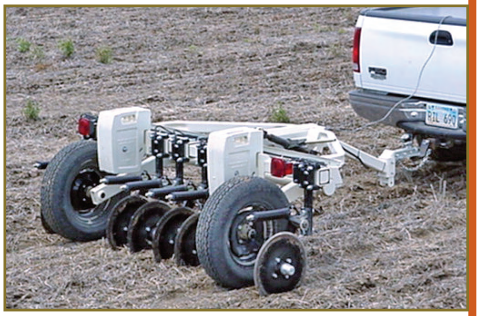
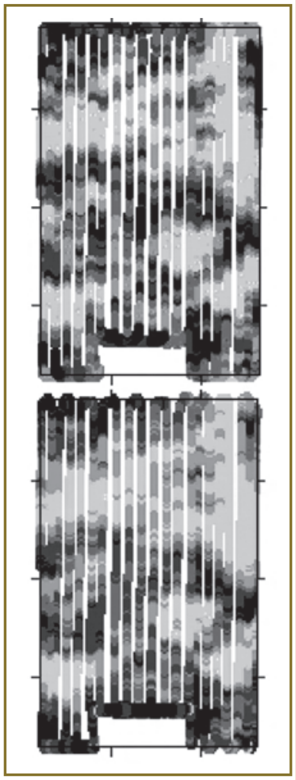


Fig. 6. Geonics EM38-MK2 (electromagnetic induction, EMI).

Fig. 7. Electromagnetic induction (EMI) and direct soil contact methods give similar results. The map above was created using EMI measurements, while the lower one was created using direct soil contact.



Two widely used EC equipment lines are produced by Veris Technologies, Inc. (Fig. 5) and Geonics, Ltd. (Fig. 6).

When used properly, the direct contact and EMI methods produce similar results (Fig. 7). For more information on the two methods, including a discussion of instrument calibration issues, see Sudduth et al. (2003).

Collecting EC Data

Producing an accurate soil EC map begins with following the manufacturer's recommended maintenance and calibration procedures. For direct contact units, that means checking continuity and isolation of the electrodes, at least on a weekly basis. Most EMI units require daily calibration, and some models may require more frequent calibration due to instrument drift (Sudduth et al., 2001).

Typically, EC data are collected by consultants and growers on an approximately 60′ transect width. This swath width is adequate to accommodate the spatial structure of most fields. It may be advantageous to map more densely, based on intensity of field management, or if variability caused by management or land use is present. In loess-formed western soils, wider transects of 125 to 150′ have been found to be adequate (Farahani and Flynn, 2006). Speed is typically 8 to 15 mph. As swath width and speed are determined, it is important to remember that an EC map is typically a one-time investment, meaning the cost can be amortized over several years. In addition, the data collected may affect the production of many years of crops. For these reasons, it is important to collect high-quality EC data.

Viewing EC Data

The objectives for viewing EC maps will vary with consultant and grower. Some approaches automate the process of moving from EC data collection to soil sampling, and the step of reviewing the map is virtually eliminated. Other approaches involve the grower extensively, relying on his field knowledge to help interpret patterns visible on the EC map, and suggesting site-specific management strategies for each zone. Regardless of the precision program, here are some guidelines for effective map display:

1. Soil texture is a continuum, and in most cases, soil EC data should be displayed with no artificially imposed breaks. Most mapping

software has an option called “equal number,” which divides the data into ranges containing an equal number of EC points in each range. Another effective data display method is standard deviation. Both of these assume the data are normally distributed—a bell-shaped curve. Typically, three to five ranges are adequate to display the soil EC pattern. Figure 8 shows an EC dataset from an Iowa field displayed with three, five, and seven ranges. The basic pattern is evident on the map with only three ranges, and doesn’t change significantly as the number of ranges increases. The detail required will depend on several factors, such as cost of sampling, variable rate equipment responsiveness, and input costs.

2. If data are not normally distributed, such as when a field includes saline areas, it may be advantageous to classify the ranges so that the zone of suspected salinity is delineated. Since saline seeps frequently have EC values above 100 mS/m, EC ranges can be set up accordingly (Fig. 9).

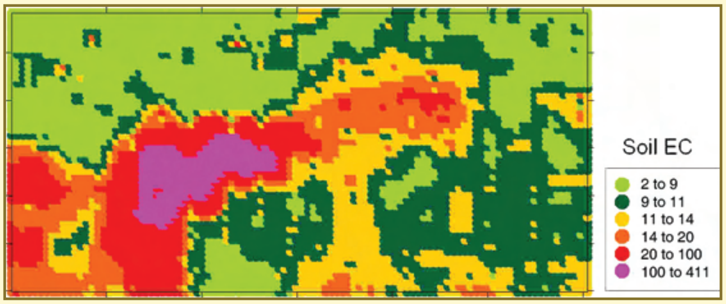


Fig. 9. Area above 100 mS/m is suspected saline seep.

3. If input from a grower is important, displaying EC data over an elevation map may be helpful in confirming characteristics and generating site-specific strategies (Fig. 10). Many software packages, including Surfer (Golden Software, Golden, CO), have three-dimensional capability.

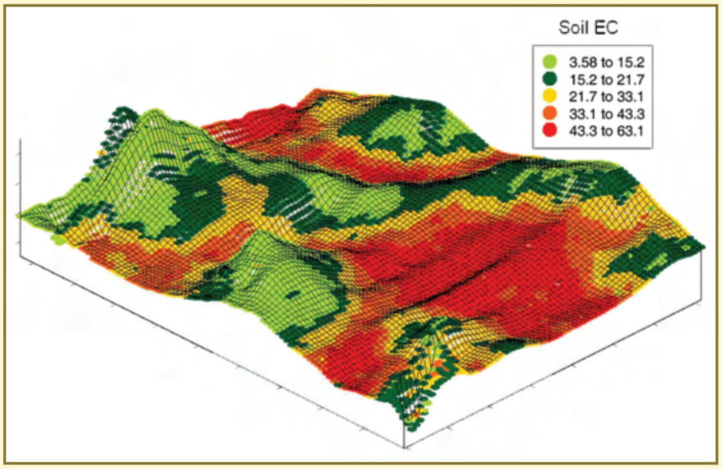


Fig. 10. Electrical conductivity data displayed over a three-dimensional elevation map.

4. Reviewing maps for data quality is important. Any unnatural pattern in the map, such as streaks, offsets, and noise, alerts the consultant and grower of a possible problem. The exception would be

Fig. 8. Iowa data set displayed with different colors and ranges. Contrasting soils are evident even with only three colors.

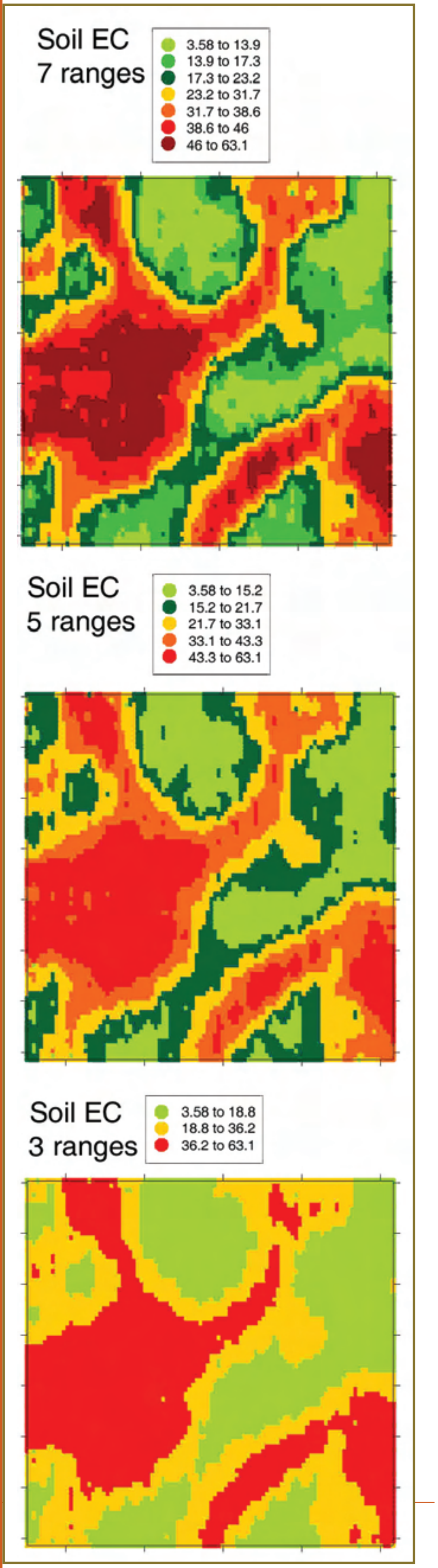
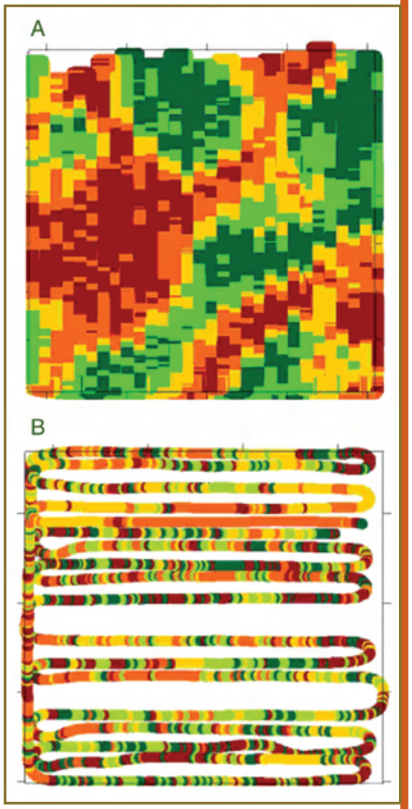


Fig. 11. (A) GPS offset problem—note the "saw-tooth" pattern. (B) Major malfunction—there is no spatial structure evident.



artificial patterns from land leveling or other soil-changing human intervention. It is important to view raw, unprocessed data, since interpolation techniques can smooth problem data into maps that appear acceptable.

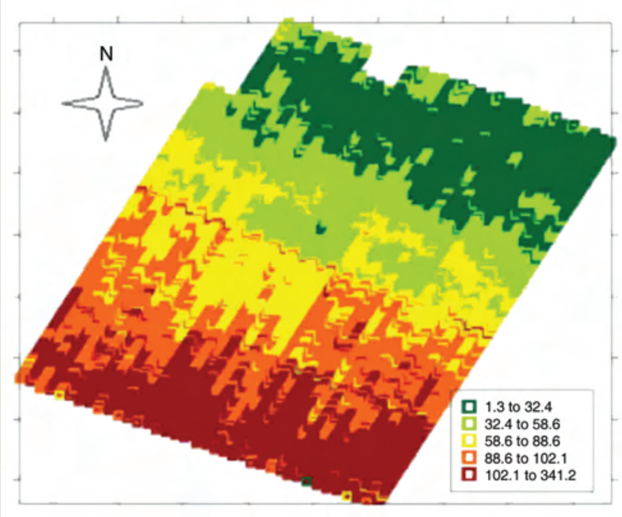
Generally, data problems are caused by equipment malfunction or soil condition variability. Equipment malfunctions include GPS offset (Fig. 11A) and electronic breakdowns (Fig. 11B).

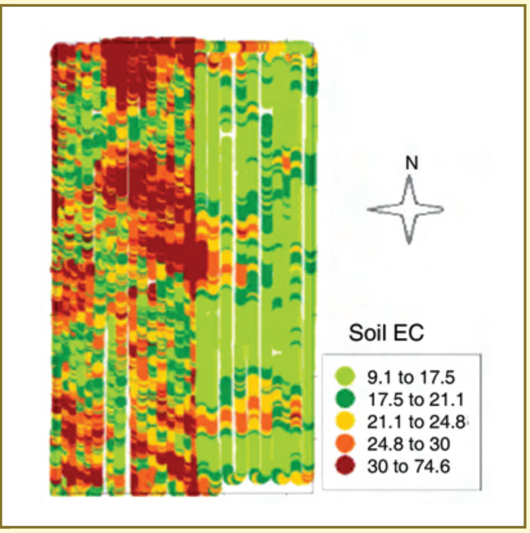
Soil condition issues are more difficult to detect. These are variations within the field caused by management-related soil temperature and soil moisture variations. For example, in a natural state, sandy areas of a field will hold less moisture than clay areas, and have lower conductivity. However if only a part of the field is irrigated, the conductivity of the wet sand is elevated, perhaps even above the conductivity of the nonirrigated clay area. Previous cropping patterns may have a similar effect, if part of a field was in a crop that used more soil moisture than another part of the field (Fig. 12. Soil temperature is another issue. Warm soil is more conductive than cold soil. When part of a field is tilled, exposing the bare soil to sunlight, it may have a higher temperature than an un-tilled part of the field (Fig. 13).

In general, high quality EC maps should have spatial structure, with natural soil zones evident. They should have good pass-to-pass repeatability; with adjacent transects showing related values.

Fig. 12. (below) North half of this field had recently been cropped, while south half was left fallow. Difference in moisture results in lower conductivity on north half.

Fig. 13. (below right) West half of this field had been tilled, warming the soil. Warmer soils are more conductive, resulting in a shift to higher EC on the west half.

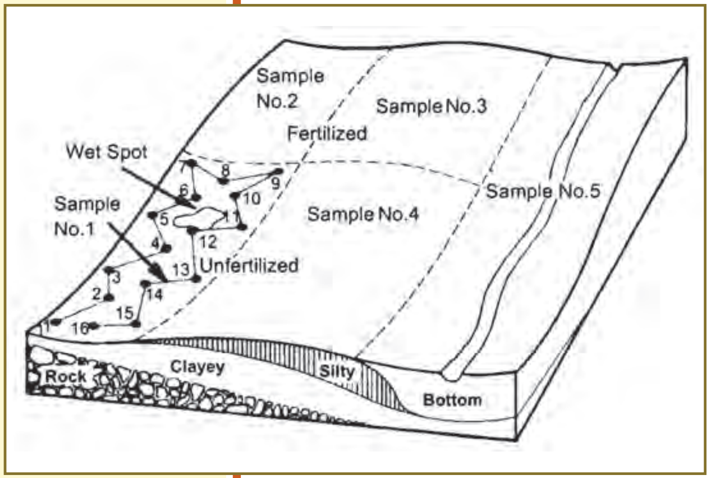




Uses of EC Maps

For soil EC maps to have value, they must be applied to the task of improving crop production and input use efficiency. The most common application for EC maps is to set up zones for soil sampling and variable rate prescriptions. The concept of management zones is not new. Many extension bulletins have advised sampling areas of a field based on visible differences (Fig. 14). Because soil EC arrays map subsurface characteristics, zones can now be delineated from factors not readily apparent.

Fig. 14. Soil sampling zones (Oklahoma State Univ. Cooperative Extension Bulletin 2207).



When using soil EC maps to create zones, several factors must be considered in using the EC data:

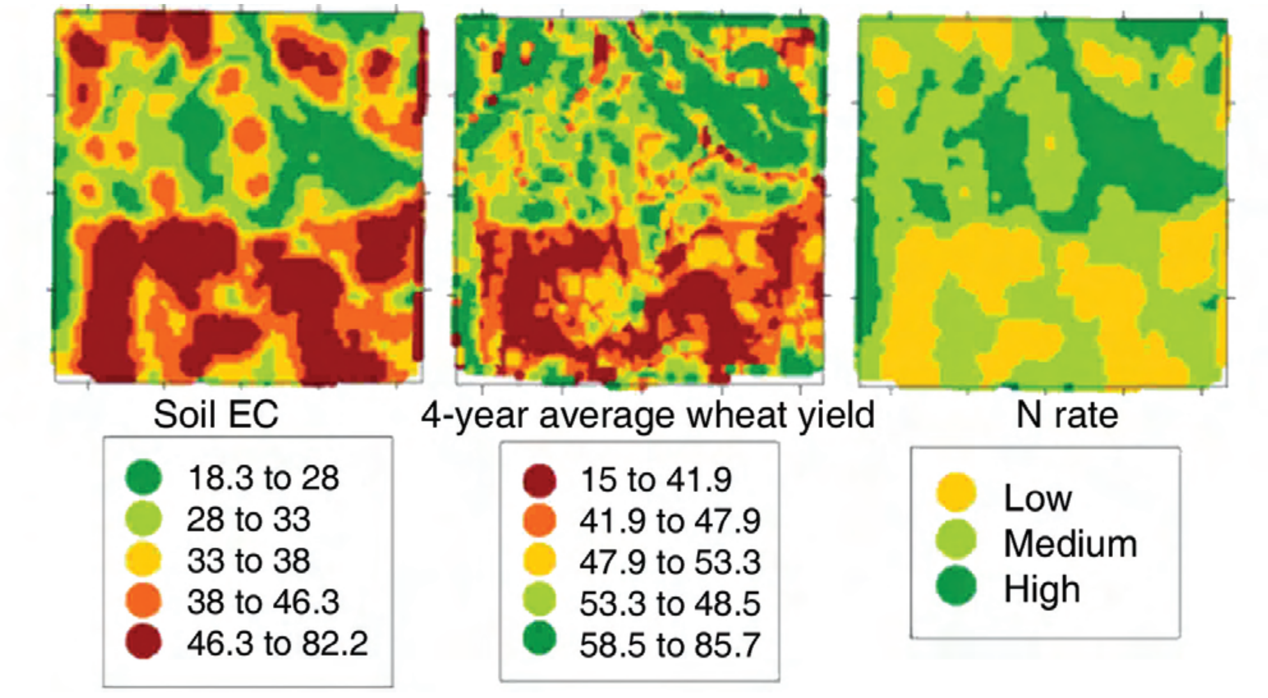
What is the strength of the relationship between EC and the inputs being managed?

The theory underlying management zones is the assumption that the property of interest is relatively consistent within each zone. Some relationships between EC and the property of interest can be direct. For example, suppose you want to determine a variable rate prescription for seed population, based on soil texture and water-holding capacity variability derived from EC zones. In this case the expectation that soil texture is consistent within an EC zone is reasonable. On the other hand, soil test phosphorous levels within an EC zone would be expected to exhibit considerable variability because there is no direct relationship between EC and phosphorus. There may be an *indirect* relationship due to the variability in use and storing of phosphorus, which is related to yield variability often caused by soil texture differences. In the case of phosphorus, the use of EC-based zones requires thorough sampling of each zone because it is likely there is variability in soil test P within each zone. In general, the less direct the relationship to EC, the greater the need for more extensive ground-truthing and soil sampling.

What is the availability of auxiliary data to layer with the EC map?

For example, aerial images showing historical information such as previous building sites and livestock feeding areas can be used to guide additional soil samples. Yield or crop image data help show the effects of soil properties on crop production, with EC maps confirming that soil properties are the primary cause of the yield pattern. Inputs can then be varied according to the combination of the two layers (Fig. 15). The relationship between EC and yield is the strongest when crops are water-limited (Doerge et al., 1999).

Fig. 15. Proposed nitrogen prescription, based on historical productivity with a close correlation to soil EC-defined zones.



Is the site-specific management based on sound agronomic principles? Is the use of soil EC applied appropriately?

Remember that site-specific applications that include EC are in actuality decisions based on a soil physical property, with soil EC maps merely delineating the pattern of that soil property. Electrical conductivity maps are being used in a wide range of site-specific management applications (Table 1).

Table 1. Various applications of soil EC in site-specific management.

Input	Site-specific management objective	Soil EC role
Corn population	match population to soil's productive potential	Increased EC values relate to increased clay contents. In claypan soil regions a lower population is applied to high EC soils. In other regions, populations are raised on finer textured soils.
Soybean population	lower population on more productive soils (to prevent lodging)	EC maps identify yellow clay knobs and nearby depositional areas. Populations are increased on the eroded hills and reduced on the more productive soils
Nitrogen	determine rates from soil samples	EC maps along with topography and crop yield data are clustered into sampling zones
Nitrogen	meet yield goal	EC maps confirm soil as cause of yield variation. N rates are based on yield history from yield data, applied to areas defined by EC map
Nitrogen	avoid excessive vegetative growth (e.g., cotton)	EC maps suggest areas prone to N carryover and rank growth. Consultant and grower devise prescription according to the EC map and their expectation of N carryover
Lime, gypsum, P, K other nutrients	determine rates from soil samples	EC maps along with other available data are used to select sampling sites
Irrigation water	optimize soil moisture sensors	EC maps guide the positioning of soil moisture sensors to ensure that moisture data are representative of the field
Irrigation water	determine water-holding capacity in permanent crops	EC maps guide the design of the irrigation system to match water rates to water-holding capacity
Irrigation water	determine water-holding capacity and field crops	EC maps guide the prescription for the variable-rate pivot to match water rates to water-holding capacity
Nematicides	identify how soil texture affects nematode activity	EC maps identify areas of coarse texture and suggest sites for nematode sampling
Cultivars	identify how productivity of cultivars varies by soil property (e.g., in grapes, tree fruit, corn, soybeans, etc.)	EC maps and ground-truthing provide rationale for cultivar placement
Soil amendments	increase water-holding capacity of coarse soils by addition of organic matter and hydrating polymers	EC maps show areas of coarse soil texture
Land use	identify parts of fields that are more or less suitable for cropping; make decisions on building sites, land retirement, and other options	EC maps help identify physical features such as shallow soils, which may be unsuitable for crop production

Conclusions

Soil EC is a rapid and relatively low-cost method of identifying soil variability patterns. Its depth of investigation, permanence, and relationship to crop growth factors make it a valuable layer to include in precision agriculture management. Data quality is a concern, as there is no field reference measurement available. This places a greater emphasis on proper maintenance and calibration of EC mapping equipment and understanding the effects soil conditions have on EC readings. There are a wide variety of site-specific applications that use EC maps, and these are tailored by local growers and consultants to local crop production and soils constraints.

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