Using Soil Sensors to Assess Soil Salinity

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A tractor pulling a sensor that measures apparent electrical conductivity (ECa). Photo courtesy of Rintaro Kinoshita and originally published here: https://bit.ly/3BwSIPO

This article is reproduced from Chapter 6 of the new book, *Salinity and Sodicity: A Growing Global Challenge to Food Security, Environmental Quality and Soil Resilience*, in a slightly modified form. The book is available for purchase from Wiley.com or Amazon.com. The article covers the use of electromagnetic (EM) sensors for measuring apparent electrical conductivity (EC_a). In the field, electrical conductivity (EC) can be measured by two primary approaches: physical contact and electromagnetic (EM) induction. With physical contact, a current is injected into the soil, and the detector measures the resulting voltage. An EM meter does not make direct contact but uses a coil to produce an EM field. A sensor then measures the soil-induced changes to the original EM field. Both types of sensors measure the EC_a, which is different from laboratory-derived EC values. When using EC_a sensors, it is important to remember that they are sensitive to many factors, including salinity, soil moisture, bulk density, soil texture, and temperature. The purpose of this article is to provide an overview on the use of EM sensors to provide examples on the use of these sensors in the field. Earn 1.5 CEUs in Soil & Water Management by reading this article and taking the quiz at https://web.sciencesocieties.org/Learning-Center/Courses

An Introduction to Electromagnetic Sensors

Electrical conductivity (EC) is an intrinsic property of soil and is affected by many soil properties (Clay et al., 2001; Heilig et al., 2011; Logsdon, 2008; McNeill, 1992; Sudduth et al., 2005). One of the properties that affects soil electrical conductivity is the concentration of the cations and anions in the soil solution. Some of these ions are Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+}. As discussed in Chapter 4 [of the new *Salinity and Sodicity* book], laboratory measurement of the soil EC involves multiple steps, including collecting, drying, grinding, and mixing the soil with water. The EC soil water solution is then measured with a meter that quantifies the ability of a solution to transmit an electrical current. The ability of the solution to transmit an electrical current increases with ion concentration. Because different measurement approaches provide different EC values, it is important to consider the measurement approach when interpreting the values.

In general, within a measurement approach, the higher the EC value, the greater the salt concentration in the soil. Electrical conductivity can be measured in the field or laboratory. Field measurements are generally reported at apparent electrical conductivity (EC_a) whereas laboratory measurements are reported as EC_e or EC1:1. Field measurements of EC_a complement and do not replace the laboratory measurement of EC.

Laboratory Measurements of Electrical Conductivity

Electrical conductivity measurements conducted in the laboratory can be combined with the measurement of K+, Na+, Ca2+, and Mg2+ to assess the risk of soil dispersion. In general, the higher the Na+ concentration, the higher the dispersal risk. However, this risk may be tempered if other soil cations are also present in high quantities. The classical approach to assess the risk of soil dispersion from high Na+ concentrations is to measure the exchangeable sodium percent (ESP) (100×Na/CEC). However, because the measurement of ESP is expensive, alternative techniques have been developed (see Chapter 4 of the new Salinity and Sodicity book). The most common approaches are to determine the sodium adsorption ratio (SAR) or sodium percentage (%Na). In the laboratory, the measurement of EC is attributed only to differences in the concentrations of the cations and anions in the soil solution, whereas in the field, EC_a measurements can be influenced by many factors, including total dissolved salts, soil texture, bulk density, and temperature (He et al., 2018; Doolittle & Brevik, 2014). Because in-field EC_a measurements are relatively inexpensive, they are well suited for conducting an initial assessment of salinity spatial variability. However, because many factors can influence EC_a, care must be used when interpreting this information.

Field Measurements of Apparent Soil Electrical Conductivity

There are a variety of sensors designed to measure EC in the field. These sensors may use different technologies. For example, the Veris MSP3 (Veris Technology) system generates a small electrical current that is transferred into the soil through a pair of electrode coulter disks. A second pair of coulters then measures the drop in voltage, which is proportional to the soil's EC. A second method is utilized by an EM sensor (see chapter 5 of the *Salinity and Sodicity* book). This sensor does not come into physical contact with the soil, and it uses a coil to induce an EM field into the soil. The EC_a is based on changes in the EM field. Electromagnetic sensors range from mobile to stationary, and they can be configured in multiple ways (Mat Su & Adamchuk, 2023). When comparing these two approaches, it is important to consider that they provide slightly different values (Mat Su & Adamchuk, 2023).

In the laboratory, the electrical conductivity of a solution is measured, whereas in the field, the ability of the soil to conduct an electrical current or modify and EM field is measured. These measurement approaches are generally correlated to each other; however, the relationship is dependent on temporal and spatial changes of many factors, including soil temperature, moisture, bulk density, and texture.

The Seven Steps for Using an Apparent Electrical Conductivity Sensor to Assess Soil Salinity

Soil sensors that measure EC_a have been used to better understand the soil spatial and temporal variability.

These sensors can be used to identify soil zones with high bulk densities, soil textural changes, and high salt concentrations. The primary benefit of these sensors is that they provide an inexpensive rapid assessment that is easy to interpret. By combining EC_a sensor information with chemical analysis, locations, and elevation information, useful maps can be created. However, because EC_a sensors are sensitive to many factors, EC_a cannot be directly converted to EC_e. To use EC_a to assess salinity issues, a seven-step process should be used. In this example, you are asked by a client to help determine the problems and solutions in a field that has a patchwork of low and highly productive areas.

Step 1: Determine the Likely Problem

Visiting a site and obtaining site histories is an important first step in the creation of a remediation plan that removes excess salts from the soil and improves plant and soil health. This information may include identifying the location, conducting a farmer interview to obtain prior histories, making targeted measurements of the soil's physical properties, analyzing historic yield monitor and remote-sensing data, and identifying the soil types and chemical characteristics. For example, the image shown in Figure 1 highlights areas with different EC_a values. However, prior to assuming that salinity or sodicity are the primary problems, it is important to look for evidence supporting this suspicion. For example, does the soil classification suggest that it is a salt-affected soil (Chapter 3 of the *Salinity and Sodicity* book), or does prior soil sampling indicate that the EC or %Na are relatively high?

Figure 1. Inspecting a site for salinity and sodicity problems. Photo courtesy of Cheryl Reese, South Dakota State University.

In the information collection stage, it is important to consider that multiple problems can have similar symptoms. For example, compaction by itself or when combined with salinity and sodicity can produce similar symptoms. A rapid approach to assess compaction is to determine the soil texture, friability, and penetrometer resistance (Kumar et al., 2016). Soil texture is the relative amount of sand, silt, and clay, whereas friability is the tendency for a soil to crumble into smaller fragments. Penetrometer resistance is the resistance of soil to the insertion of a probe. Friability and penetrometer resistance decrease with increasing soil water. Sodium can affect both values by dispersing the soil aggregates.

The measurement of the soil bulk density and water infiltration can provide additional information. Bulk density is the dry weight of soil per unit volume of soil, and relative water infiltration can be measured by digging a small hole and measuring how fast the water disappears. Sodium-dispersed soils can have high bulk densities and low water infiltration rates. When inspecting the site, it is important to collect a soil sample for laboratory analysis to determine the soil EC and the amount of exchangeable Na+ on the exchange sites (ESP, SAR, or %Na). See Chapter 4 [of the new Salinity and Sodicity book] for details on chemical analysis.

Step 2: Select a Sensor and Measurement Approach

To develop corrective solutions, the source and extent of the problem must be identified. There are many approaches to assess the extent of a salinity and sodicity problem, including analyzing soil samples collected from a grid design for EC_e and ESP or using an EM sensor to create an EC_a map (Doolittle & Brevik, 2014). If you choose to collect and analyze soil samples for EC, then a soil-sampling protocol must be selected. There are many options to collect soil samples, ranging from composite soil samples from management zones to grid soil sampling (Clay & Carlson, 2016). When selecting a sensor, consider costs, skill requirements to collect the samples, and desired outcomes. Whenever possible, the sampling protocol should match the problem. For example, if the problem is concentrated in the surface soil, then the sensor should concentrate on the soil surface, whereas if the problem is concentrated at a lower soil depth, then a sensor should be selected that measures deeper in the soil profile (Corwin & Yemoto, 2020). Clues about the location of the salinity and sodicity problem may be provided in the soil name (Chapter 3 of the *Salinity and Sodicity* book), inspecting the site, or by collecting soil samples from targeted areas for analysis.

That's not snow—it's salt. Some areas on the righthand side of this photo are starting to look a bit better after four years. This photo, courtesy of Sharon Clay, originally published in the October 2021 CSA News as part of research published in the Journal of Environmental Quality by Fiedler et al. (2021): https://doi.org/10.1002/jeq2.20223.

Step 3: Calibrate the Sensor

All data collection protocols start with ensuring that the equipment is well-maintained and calibrated. To assess temporal and spatial changes in soil salinity and sodicity, EC_a sensors should be calibrated prior to use. Calibration can be conducted by at least two approaches. The first approach is to use the sensor to measure EC_a followed by collecting soil samples from the study area, that are analyzed for EC_e, followed by comparing the EC_a and EC_e values. The second approach is to follow the manufacturer calibration procedures. It is essential to standardize the device to a uniform output to accurately make comparisons from one year to the next. Temperature calibrations may also be required.

Step 4: Conduct the Survey

Conducting a survey starts with creating a sampling design. The sampling design should be based on identifying the extent of the problem. Two basic approaches can be used to conduct the survey. In the first approach, a stop-and-go measurement approach is used. In a stop-and-go approach, a grid is overlayed on the field. At each grid point, the location and elevation are measured with a global position satellite (GPS) system, and a sensor measures the EC_a. At selected sampling points, a soil sample is collected that will be analyzed for EC using an appropriate protocol.

In the second approach, an EM sensor and GPS system is driven across a field. This sensor measures EC_a, elevation, and location/elevation simultaneously. When using this approach, the surveyor selects the distance between the transects. Where possible, the transects should be perpendicular to elevation. The survey should avoid field edges because these areas often are compacted or have high EC resulting from runoff from roads.

Step 5: Analyze the Soil Samples

Soil samples should be analyzed as soon as possible using an appropriate protocol. In most situations, the samples should be analyzed for EC, pH, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+} and for the relative amount of Na^+ on the soil's cation exchange sites. The ratio between Na and the CEC is the ESP. However due to cost, the ESP value is often replaced by the SAR or %Na values. Additional information for analyzing soil samples is available in Chapter 4 (of the new *Salinity and Sodicity* book), and information about GPS is available in Shannon et al. (2018).

Step 6: Convert EC_a to EC_e or $EC_{1:1}$

After the EM survey has been conducted and the associated soil samples are analyzed, the relationship between EC_a and EC_e/EC of a 1:1 soil/water mixture ($EC_{1:1}$) can be determined. For this analysis, it might be necessary to separate the field into management zones. Management zones can be based on a soil survey or elevation map. Across the field or within a zone, determine the relationship and equation relating EC_a to EC_e or $EC_{1:1}$. Based on this relationship, convert the EC_a to EC_e or $EC_{1:1}$.

Step 7: Graphic Display

One of the goals for conducting the survey is to assist in soil sampling and implementing remediation treatments. Prior to displaying the data set, check it for errors that need to be removed. When displaying the map, let the software process the data and create a map. When using this approach, it is important to compare the map with the field and the producer's knowledge. In many situations, overlaying the EC_a map on an elevation map makes sense (Figure 2). Low areas in production fields often have high ECa values. High values are often linked to areas with high EC_e values or contain compacted soil zones, whereas low values may be associated to coarse-textured soil. If the maps are not useful, try adjusting the boundary EC_e values of the zones. There are several approaches to convert EC_a to EC_e. The most common is to determine the relationship between EC_a and EC_e and make the conversion based on this relationship. This generally involves determining the EC_a and EC_e values at selected points, followed by determining the equation that relates the two values.

In summary, EM surveys are not designed to replace but to compliment traditional plant and soil health measurements. To create a useful EM map, technical know-how is required about GPS, the EM sensor, and data processing. Electromagnetic values are influenced by many factors, such as texture, moisture content, salt concentration, temperature, and bulk density, so when converting EC_a to EC_e, it is important to understand relationships among these parameters. If more than one property is found to be highly correlated to ECa, a multivariate model may be required. A sensor that measures EC_a is a relatively low-cost approach for creating directed soil maps, and when the sensor is maintained, standardized, and calibrated, it can be used to create management zones.

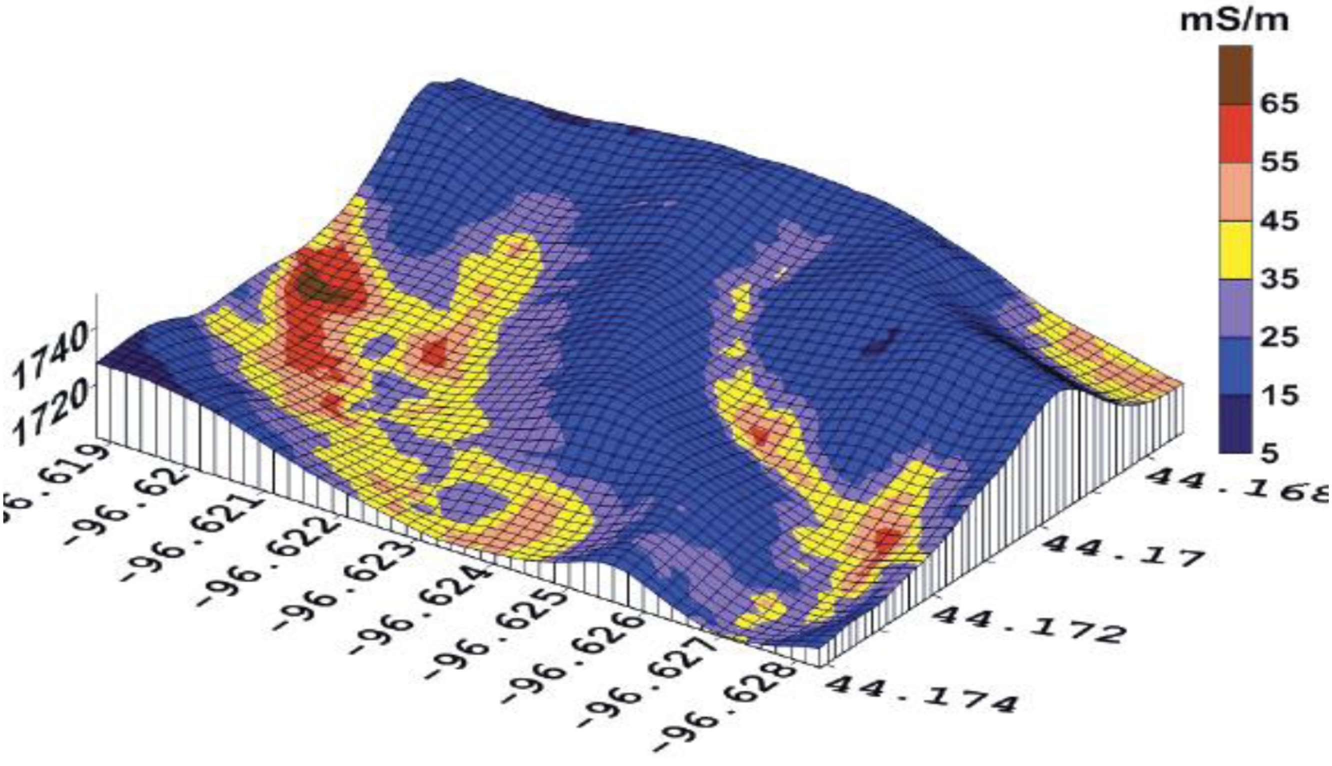


Figure 2. Apparent electrical conductivity (EC_a) overlayed on an elevation map. This map was obtained by pulling an electromagnetic (EM) sensor behind a vehicle as it drove across a field. This map suggests that ECa varies across the field and that the footslope zone generally had higher values than backslope zones. However, because EM sensors are

affected by many factors, to confirm that the variation was salts, soil samples were collected and analyzed for EC of a 1:1 soil/water mixture (EC1:1).

Examples of two types of soil electrical conductivity sensors: (a) can be used in the field, greenhouse, or laboratory and (b) laboratory only. Photo from Chapter 4, "Laboratory Methods for Determining Salinity and Sodicity," of the new book, Salinity and Sodicity: A Growing Global Challenge to Food Security, Environmental Quality and Soil Resilience.

Case Studies on the Use of Apparent Electrical Conductivity Information

He et al. (2018) collected 1,088 soil samples from a 12.2- by 12.3-m grid within a 8.1-ha (20 ac) field. Soil samples were analyzed for $EC_{1:1}$, $pH_{1:1}$, soil dispersion, and the concentration of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}. At the sampling points, EC_a was measured with an EM 38 when the sensor was in the horizontal and vertical dipole modes. Soils at the North Dakota site were Natruaquoll and Calciaquolls. There was a strong correlation between apparent horizontal dipole EC (EC_{ah}) and %Na (r^2 = 0.71), ECah and ECe (r^2 = 0.79), and EC_e and %Na (r^2 = 0.77).

A soil apparent electrical conductivity (ECa) mapping system towed behind a utility vehicle in a field of corn stubble. Photo courtesy of the USDA-NRCS Soil Survey Manual.

All geo-referenced data were entered into the ArcGIS 10.0, and interpolation maps of %Na, $EC_{1:1}$, EC_{ah}, and apparent vertical dipole EC were prepared using the ordinary inverse-distance-weight interpolation. Finally, a management zone map was created in Management Zone Analyst 1.0.1 using the EC_{ah} and %Na data sets. After the zones were delineated, composite soil samples from each zone could be collected to determine the gypsum requirement.

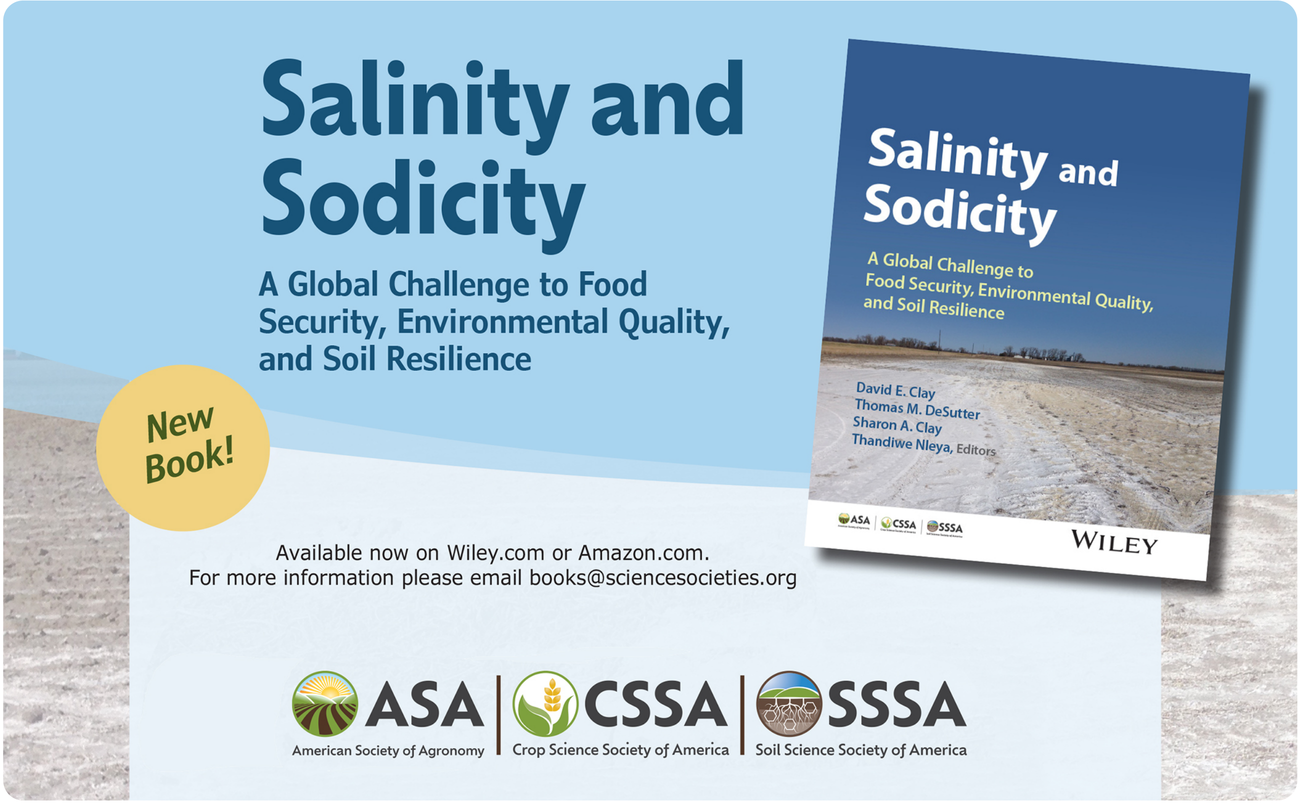
Presence of salt in soil cores collected beneath the root zone. Photo originally published in the August 2018 CSA News and contributed by the authors of this Agronomy Journal research published by Butcher et al. (2018): https://doi.org/10.2134/agronj2017.10.0619.

Amezketa (2007) evaluated the ability of using EC_a information for mapping saline/sodic soils in Navarre, Spain. The fields were underlain by saliferous rock strata, and EC_a was measured from an orthogonal grid that varied depending on the field size. Soil water content was approximately field capacity, and EC_a values were corrected to a reference temperature of 25°C (77°F). About 10–30 soil-sampling sites that corresponded to a full range of EM 38 measurements were surveyed within each field (site selected with the help of ESAP-RSSD program). Multiple linear regression (preloaded prediction model) included in ESAP-calibrate was then used to estimate the calibration equation by pairing EC_a readings with laboratory-analyzed soil property data. The EC_a and SAR values were strongly correlated (*r* >0.91). These results were attributed to autocorrelation (r >0.93) between EC_e and SAR in all fields. The calibration models accounted for 87% of the observed variability in salinity and 84% in sodicity. Soil salinity and sodicity raster maps were prepared by IDS interpolation of EM-estimated profile average EC_e and SAR values.

Ganjegunte et al. (2013) used an EM sensor to measure salinity and sodicity in turfgrass soil watered with saline water. Tall fescue (*Lolium arundinaceum*) and Kentucky bluegrass (*Poa pratensis*) were irrigated with water that had EC values of 0.6 and 2.98 dS/m. At the end of the study, EC_a was measured using an EM 38 only in the horizontal coil configuration. Locations and ECa were measured every 4.3 m (14.1 ft) in transects separated by 20 m (65.6 ft). After completing the survey, 24 locations were selected for soil sampling. At each point, soil samples were collected in 15-cm (6 inch) increments to a depth of 75 cm (29.5 inches). Soil samples were analyzed for EC_e, pH, concentration of Na^+, Ca^{2+}, and Mg^{2+} using plasma spectroscopy and for SAR. Based on a strong relationship between EC_a and EC_e, point kriging using a linear model was used to create an EC_e map based on the EC_a data. These findings showed that kriging can be used to create an EC_e map based on EM data.

Summary

Electrical conductivity can be measured in the field continuously using either physical contact or EM induction. With physical contact, an electrical current is injected into the soil, and the detector measures the resulting voltage, whereas an EM meter does not make direct contact but instead uses a coil to produce an EC field. Both sensors measure the EC_a, which is different from laboratory-derived EC values. This article discussed the feasibility of using laboratory measurements to convert field-measured EC_a data into EC_e values. A seven-step process for this site-specific conversion was proposed. The primary benefits of the EC sensor approach are the low cost and the increased speed at which useful information can be collected. As a result, the EC sensor approach reduces the cost of conducting a salinity and sodicity survey.



Acknowledgments

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References

Amezketa, E. (2007). Use of an electromagnetic technique to determine sodicity in saline-sodic soils. Soil Use and Management, 23, 278–285.

Clay, D. E., & Carlson, C. G. (2016). Precision soil sampling. In D. E. Clay, C. G. Carlson, S. A. Clay, & E. Byamukama (Eds.), iGrow corn: Best management practices. South Dakota

State University.

Clay, D. E., Chang, J., Malo, D. D., Carlson, C. G., Reese, C., Clay, S. A., Ellsbury, M., & Berg, B. (2001). Factors influencing spatial variability of soil apparent electrical conductivity. Communications in Soil Science and Plant Analysis, 32(19–20), 2993–3008.

Corwin, D. L., & Yemoto, K. (2020). Salinity: Electrical conductivity and total dissolved solids. Soil Science Society of America Journal, 84, 1442–1461.

Doolittle, J. A., & Brevik, E. C. (2014). The use of electromagnetic techniques in soil studies. Geoderma, 223, 33–45.

Ganjegunte, G., Leinauer, B., Schiavon, M., & Serena, M. (2013). Using electro-magnetic induction to determine soil salinity and sodicity in turf root zones. Agronomy Journal, 105(3), 836–844.

He, Y., DeSutter, T., Norland, J., Chatterjee, A., Casey, F., & Clay, D. E. (2018). The measurement, prediction, and development of soil management zones in low-relief sodic soils. Precision Agriculture, 19(5), 858–875.

Heilig, J., Kempenich, J., Doolittle, J., Brevik, E. C., & Ulmer, M. (2011). Evaluation of electromagnetic induction to characterize and map sodium-affected soils in the northern Great Plains. Soil Survey Horizons, 52(3), 77–88.

Kumar, S., Clay, D. E., & Carlson, C. G. (2016). Soil compaction impact on corn yield. In D. E. Clay, C. G. Carlson, S. A. Clay, & E. Byamukama (Eds.), iGrow corn: Best management practices. South Dakota State University.

Logsdon, S. D. (2008). Soil science: Step-by-step field analysis. ASA, SSSA, & CSSA.

Mat Su, A. S., & Adamchuk, V. L. (2023). Temporal and operational instability of apparent soil electrical conductivity. Frontiers in Soil Science, 3, 1137731.

McNeill, J. D. (1992). Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters. In G. C. Topp, W. D. Reynolds, & R. E. Green (Eds.), Advances in measurement of soil physical properties: Bringing theory into practice (pp. 209–229)). John Wiley & Sons.

Shannon, D. K., Clay, D. E., & Kitchen, N. R. (2018). Precision agriculture basics. ASA, SSSA, & CSSA.

Sudduth, K. A., Kitchen, N. R., Wiebold, W. J., Batchelor, W. D., Bollero, G. A., Bullock, D. G., Clay, D. E., Palm, H. L., Pierce, F. J., Schuler, R. T., & Thelen, K. D. (2005). Relating apparent electrical conductivity to soil properties across the north-Central USA. Computers and Electronics in Agriculture, 46(1–3), 263–283.

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1. **How do laboratory and in-field measurements of EC differ?**
   a. Field measurements are reported as EC_e, and lab measurements are reported as EC_a.

b. Field measurements are reported as EC_a, and lab measurements are reported as EC_e.
c. Lab measurements are more accurate than field measurements.
d. Field measurements are not influenced by total dissolved salts.

2. **The concentration of anions in the soil solution does NOT affect soil electrical conductivity.**
   a. True.
   b. False.

3. **How are EC and direct contact sensors different?**
   a. Direct contact sensors do not measure EC_a.
   b. EC sensors do not measure EC_a.
   c. An EM meter does not make physical contact with the soil while a direct contact sensor does.
   d. A direct contact sensor measures EC_e values in the field.

4. **In the Veris MSP3 system, what measurement is proportional to the soil's EC?**
   a. The drop in voltage.
   b. The concentration of K^+ cations in the soil.
   c. The soil temperature.
   d. The concentration of Mg^{2+} cations in the soil.

5. **What is an important first step in creating a remediation plan to remove excess salt from soil?**

a. Conducting a farmer interview.
b. Identifying the soil type.
c. Analyzing historical data.
d. A combination of the above.

6. **How can you calibrate an EC_a sensor?**
   a. By using the sensor to measure EC_a followed by collecting soil samples from the study area that are analyzed for EC_e, then comparing EC_a and EC_e.
   b. By following the manufacturer calibration process.
   c. a or b
   d. Calibration is not necessary when making temporal or spatial comparisons of salinity and sodicity.

7. **What is the ratio between Na and the CEC known as?**
   a. The electromagnetic percent.
   b. The soil adsorption ratio.
   c. The exact sodium percent.
   d. The exchangeable sodium percent.

8. **___ areas in production fields often have ___ EC_a values.**
   a. Low, high
   b. High, high
   c. Low, low
   d. There is no relation between elevation and EC_a values.

9. **When surveying, why should you avoid field edges?**
    a. These areas often are compacted.
    b. These areas often have low EC resulting from runoff from roads.
    c. These areas are often at lower elevation.
    d. These areas are often at higher elevation.

10. **An EC sensor approach can reduce the cost of a survey.**
    a. True.
    b. False.

11. **Electrical conductivity measured in the field using EM induction**
    a. involves physical contact of the soil.
    b. uses a coil to produce an EC field.
    c. provides the same values as those derived from a laboratory.
    d. cannot be measured continuously.

12. **High EC_a values in a field are often linked to**
    a. areas with low EC_e values.
    b. compacted soil zones.
    c. coarse-textured soil.
    d. None of the above.

13. **The ESP value is often replaced by the SAR or %Na values due to cost.**
    a. True.
    b. False.

14. **Which of the following statements is true, in general?**
    a. The ability of the EC soil water solution to transmit an electrical current decreases with ion concentration.
    b. The measurement field EC_a is attributed only to differences in the concentrations of the cations and anions in the soil solution and not other factors.
    c. The lower the Na+ concentration, the higher the EC.
    d. The higher the Na+ concentration, the higher the dispersal risk.

15. **Which of the following is NOT true about sensors designed to measure EC in the field?**
    a. They can be mobile.
    b. They can be stationary.
    c. They all use the same technology.
    d. Different sensors can provide slightly different values.
