Soil Salinity Measurement

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INTRODUCTION

The measurement of soil salinity is a quantification of the total salts present in the liquid portion of the soil. The measurement of soil salinity is important in agriculture because salinity reduces crop yields by 1) making it more difficult for the plant to extract water; 2) causing specific-ion toxicity; 3) influencing the soil permeability and tilth; and/or 4) upsetting the nutritional balance of plants. A discussion of the basic principles, methods, and equipment for measuring soil salinity is presented. The concise discussion provides a basic knowledge of the background, latest equipment, and current accepted methodologies for measuring soil salinity with suction cup extractors, porous matrix/salinity sensors, electrical resistivity, electromagnetic induction (EM), and time domain reflectometry (TDR).

SOIL SALINITY: DEFINITION, EFFECTS, AND GLOBAL IMPACTS

Soil salinity refers to the presence of major dissolved inorganic solutes in the soil aqueous phase, which consist of soluble and readily dissolvable salts including charged species (e.g., Na^+, K^+, Mg^{+2}, Ca^{+2}, Cl^-, HCO_3^-, NO_3^-, SO_4^{-2}, and CO_3^{-2}), non-ionic solutes, and ions that combine to form ion pairs. The predominant mechanism causing the accumulation of salt in irrigated agricultural soils is loss of water through evapotranspiration, leaving ever increasing concentrations of salts in the remaining water. Effects of soil salinity are manifested in loss of stand, reduced plant growth, reduced yields, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential making it more difficult for the plant to extract water. Salinity may also cause specific-ion toxicity or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth. Irrigated agriculture, which accounts for 35%–40% of the world's total food and fiber, is adversely affected by soil salinity on roughly half of all irrigated soils (totaling about 250 million ha) with over 20 million ha severely effected by salinity worldwide.[1] Because of these detrimental impacts, the measurement, monitoring, and real-time mapping of soil salinity is crucial to sustaining world agricultural productivity.

METHODS OF SOIL SALINITY MEASUREMENT

Historically, five methods have been developed for determining soil salinity at field scales: 1) visual crop observations; 2) the electrical conductance of soil solution extracts or extracts at higher than normal water contents; 3) in situ measurement of electrical resistivity; 4) noninvasive measurement of electrical conductance with EM; and most recently 5) in situ measurement of electrical conductance with TDR.

Visual Crop Observation

Visual crop observation is a quick and economical method, but it has the disadvantage that salinity development is detected after crop damage has occurred. For obvious reasons, the least desirable method is visual observation because crop yields are reduced to obtain soil salinity information. However, remote imagery is increasingly becoming a part of agriculture and potentially represents a quantitative approach to visual observation. Remote imagery may offer a potential for early detection of the onset of salinity damage to plants.

Electrical Conductivity of Soil Solution Extracts

The determination of salinity through the measurement of electrical conductance has been well established for decades.[2] It is known that the electrical conductivity (EC) of water is a function of its chemical composition. McNeal et al.[3] were among the first to establish the relationship between EC and molar concentrations of ions in the soil solution. Soil salinity is quantified in terms of the total concentration of the soluble salts as measured by the EC of the solution in dS m^{-1}.[2] To determine EC, the soil solution is placed between two electrodes of constant

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geometry and distance of separation.[4] At constant potential, the current is inversely proportional to the solution's resistance. The measured conductance is a consequence of the solution's salt concentration and the electrode geometry whose effects are embodied in a cell constant. The electrical conductance is a reciprocal of the resistance (Eq. 1):

$$EC_t = k/R_t \tag{1}$$

where EC_t is the EC of the solution in $dS\,m^{-1}$ at temperature t (EC), k is the cell constant, and R_t is the measured resistance at temperature t. One $dS\,m^{-1}$ is equivalent to $1\,mmho\,cm^{-1}$.

Customarily, soil salinity has been defined in terms of laboratory measurements of the EC of the saturation extract (EC_e), because it is impractical for routine purposes to extract soil water from samples at typical field water contents. Partitioning of solutes over the three soil phases (i.e., gas, liquid, and solid) is influenced by the soil–water ratio at which the extract is made, so the ratio must be standardized to obtain results that can be applied and interpreted universally. Commonly used extract ratios other than a saturated soil paste are 1:1, 1:2, and 1:5 soil–water mixtures.

Soil salinity can also be determined from the measurement of the EC of a soil solution (EC_w). Theoretically, EC_w is the best index of soil salinity because this is the salinity actually experienced by the plant root. Nevertheless, EC_w has not been widely used to express soil salinity for various reasons: 1) it varies over the irrigation cycle as the soil water content changes and 2) methods for obtaining soil solution samples are too labor, and cost intensive at typical field water contents to be practical for field-scale applications.[5] For disturbed samples, soil solution can be obtained in the laboratory by displacement, compaction, centrifugation, molecular adsorption, and vacuum- or pressure-extraction methods. For undisturbed samples, EC_w can be determined either in the laboratory on a soil solution sample collected with a soil-solution extractor or directly in the field by using in situ, imbibing-type porous-matrix salinity sensors.

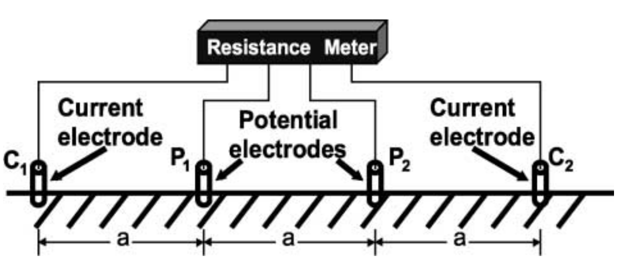

Fig. 1 Schematic of electrical resistivity of four electrodes (the Wenner array configuration). C_1 and C_2 represent the current electrodes, P_1 and P_2 represent the potential electrodes, and a represents the inter-electrode spacing. Modified from Rhoades and Halverson.[15]

There are serious doubts about the ability of soil solution extractors and porous matrix salinity sensors (also known as soil salinity sensors) to provide representative soil water samples.[6–8] Because of their small sphere of measurement, neither extractors nor salt sensors adequately integrate spatial variability;[9–11] consequently, Biggar and Nielsen[12] suggested that soil solution samples are "point samples" that can provide qualitative measurement of soil solutions, but not quantitative measurements unless the field-scale variability is established. Furthermore, salinity sensors demonstrate a response time lag that is dependent upon the diffusion of ions between the soil solution and solution in the porous ceramic, which is affected by 1) the thickness of the ceramic conductivity cell; 2) the diffusion coefficients in soil and ceramic; and 3) the fraction of the ceramic surface in contact with soil.[13] The salinity sensor is generally considered the least desirable method for measuring EC_w because of its low sample volume, unstable calibration over time, and slow response time.[14]

Electrical Resistivity

Because of the time and cost of obtaining soil solution extracts, developments in the measurement of soil EC have shifted to the measurement of the soil EC of the bulk soil, referred to as the apparent soil electrical conductance (EC_a). The apparent soil EC measures the conductance through not only the soil solution but also through the solid soil particles and via exchangeable cations that exist at the solid–liquid interface of clay minerals. The techniques of electrical resistivity, EM, and TDR measure EC_a.

Electrical resistivity methods introduce an electrical current into the soil through current electrodes at the soil surface and the difference in current flow potential is measured at potential electrodes that are placed in the vicinity of the current flow (Fig. 1). These methods were developed in the second decade of the 1900s by Conrad Schlumberger in France and Frank Wenner in the United States for the evaluation of ground electrical resistivity.[16,17]

The electrode configuration is referred to as a Wenner array when four electrodes are equidistantly spaced in a straight line at the soil surface with the two outer electrodes serving as the current or transmission electrodes and the two inner electrodes serving as the potential or receiving electrodes.[18] The depth of penetration of the electrical current and the volume of measurement increase as the inter-electrode spacing, a, increases. For a homogeneous soil, the soil volume measured is roughly Πa^3. There are additional electrode configurations that are

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frequently used, as discussed by Burger,[16] Telford et al.,[17] and Dobrin.[19]

By mounting the electrodes to "fix" their spacing, considerable time for a measurement is saved. A tractor-mounted version of the "fixed-electrode array" has been developed that geo-references the EC_a measurement with a GPS.[20–22] The mobile, "fixed-electrode array" equipment is well suited for collecting detailed maps of the spatial variability of average root zone soil electrical conductivity at field scales and larger. Veris Technologies[a] has developed a commercial mobile system for measuring EC_a using the principles of electrical resistivity.

Electrical resistivity (e.g., the Wenner array) and EM, are both well suited for field-scale applications because their volumes of measurement are large, which reduces the influence of local-scale variability. However, electrical resistivity is an invasive technique that requires good contact between the soil and four electrodes inserted into the soil; consequently, it produces less reliable measurements in dry, frozen, or stony soils than the non-invasive EM measurement. Nevertheless, electrical resistivity has a flexibility that has proven advantageous for field application, i.e., the depth and volume of measurement can be easily changed by altering the spacing between the electrodes.

Electromagnetic Induction

A transmitter coil located at one end of the EM instrument induces circular eddy-current loops in the soil with the magnitude of these loops directly proportional to the EC in the vicinity of that loop. Each current loop generates a secondary electromagnetic field that is proportional to the value of the current flowing within the loop. A fraction of the secondary induced electromagnetic field from each loop is intercepted by the receiver coil of the instrument and the sum of these signals is amplified and formed into an output voltage which is related to a depth-weighted soil EC_a. The amplitude and phase of the secondary field will differ from those of the primary field as a result of soil properties (e.g., salinity, water content, clay content, bulk density, and organic matter), spacing of the coils and their orientation, frequency, and distance from the soil surface.[23]

The two most commonly used EM conductivity meters in soil science and in vadose zone hydrology are the Geonics[b] EM-31, and EM-38. The EM-38 (Fig. 2) has had considerably greater application for agricultural purposes because the depth of measurement corresponds roughly to the root zone (i.e., 1.5 m), when the instrument is placed in the vertical coil configuration. In the horizontal coil configuration, the depth of the measurement is 0.75 m–1.0 m. The operation of the EM-38 equipment is discussed in Hendrickx and Kachanoski.[23]

Mobile EM equipment developed at the Salinity Laboratory[20,22] is available for appraisal of soil salinity and other soil properties (e.g., water content and clay content) using an EM-38. Recently, the mobile EM equipment developed at the Salinity Laboratory was modified by the addition of a dual-dipole EM-38 unit (Fig. 3). The dual-dipole EM-38 conductivity meter simultaneously records data in both dipole orientations (horizontal and vertical) at time intervals of just a few seconds between readings. The mobile EM equipment is suited for the detailed mapping of EC_a and correlated soil properties at specified depth intervals through the root zone. The advantage of the mobile dual-dipole EM equipment over the mobile "fixed-array" resistivity equipment is the EM technique is noninvasive so it can be used in dry, frozen, or stony soils that would not be amenable to the invasive technique of the "fixed-array" approach due to the need for good electrode–soil contact. The disadvantage of the EM approach would be that the EC_a is a depth-weighted value that is nonlinear with depth McNeill.[24]

Time Domain Reflectometry

TDR was initially adapted for use in measuring water content. Later, Dalton et al.[25] demonstrated the utility of TDR to also measure EC_a, based on the attenuation of the applied signal voltage as it traverses the medium of interest[26]. Advantages of TDR for measuring EC_a include 1) a relatively noninvasive nature; 2) an ability to measure both soil water content and EC_a; 3) an ability to detect small changes in EC_a under representative soil conditions; 4) the capability of obtaining continuous unattended measurements; and 5) a lack of a calibration requirement for soil water content measurements in many cases.[26]

Soil EC_a has become one of the most reliable and frequently used measurements to characterize field variability for application to precision agriculture due to its ease of measurement and reliability[27]. Although TDR has been demonstrated to compare closely with other accepted methods of EC_a measurement,[28–31] it is still not sufficiently simple, robust, or fast enough for the general needs of field-scale soil salinity assessment.[5] Only electrical resistivity and EM have been adapted for the geo-referenced measurement of EC_a at field scales and larger.[5,27] Details for conducting a field-scale EC_a survey can be found in Corwin and Lesch.[32]

[a]Veris Technologies, Salina, Kansas, USA (www.veristech.com). Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

[b]Geonics Limited, Mississauga, Ontario, Canada. Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

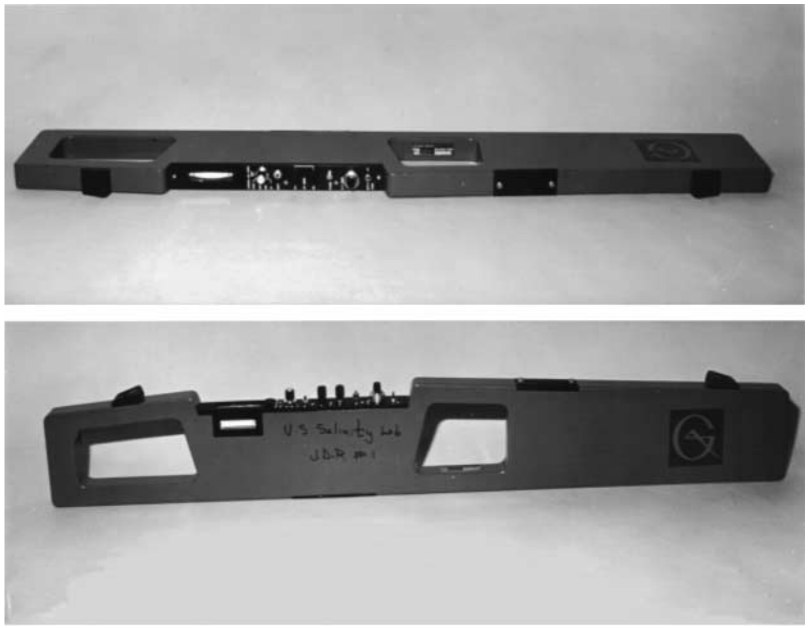

Fig. 2 Handheld Geonics EM-38 electromagnetic soil conductivity meter lying in the horizontal orientation with its coils parallel to the surface (top), and lying in the vertical orientation with its coils perpendicular to the surface (bottom). Courtesy of Rhoades et al.[5]

Fig. 3 Mobile dual-dipole EM-38 equipment for the continuous measurement of EC_a. Dual-dipole EM meter rests in the tail section or sled at the rear of the vehicle with a GPS antenna overhead at the midpoint of the meter.

FACTORS INFLUENCING THE APPARENT SOIL ELECTRICAL CONDUCTIVITY MEASUREMENT

Three pathways of current flow contribute to the apparent soil EC (EC_a) of a soil: 1) a liquid phase pathway via salts contained in the soil water occupying the large pores; 2) a solid–liquid phase pathway primarily via exchangeable cations associated with clay minerals; and 3) a solid pathway via soil particles that are in direct and continuous contact with one another.[5] Because of the three pathways of conductance, the EC_a measurement is influenced by several soil physical and chemical properties: 1) soil salinity; 2) saturation percentage; 3) water content; and 4) bulk density. The saturation percentage and bulk density are both closely associated with the clay content. Measurements of EC_a as a measure of soil salinity must be interpreted with these influencing factors in mind.

Another factor influencing EC_a is temperature. Electrolytic conductivity increases at a rate of approximately 1.9% per °C increase in temperature. Customarily, EC is expressed at a reference temperature of 25EC for purposes of comparison. The EC (i.e., EC_a, EC_e, or EC_w) measured at a particular temperature t (°C), EC_t, can be adjusted to a reference EC at 25°C, EC_{25}, using the following equations from Handbook 60:[2]

$$EC_{25} = f_t \cong \mathrm{EC}_t \quad (2)$$

where

$$f_t = 1 - 0.20346(t) + 0.03822(t^2) - 0.00555(t^3) \quad (3)$$

Traditionally, EC_e has been the standard measure of salinity used in all salt-tolerance plant studies. As a result, a relation between EC_a and EC_e is needed to relate EC_a back to EC_e, which in turn is related to crop yield.

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