



METER
ENVIRONMENT

ELECTRICAL CONDUCTIVITY OF SOIL AS A PREDICTOR OF PLANT RESPONSE

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Plants require nutrients to grow. If we fail to supply the proper nutrients in the proper concentrations, plant function is affected. Fertilizer in too high concentration can also affect plant function and sometimes is fatal. Most of us have had the experience of fertilizing some part of a lawn too heavily, perhaps by accident, and killing grass in that part of the lawn. Generally, it isn't the nutrients themselves that cause the damage, it is their effect on the water. Salt in the water reduces its water potential making it less available to the plant. The salt, therefore, causes water stress in the plant.

Salt in soil comes from the fertilizer we apply, but also from irrigation water and dissolving soil minerals. Relatively small amounts are removed with the plants that are harvested, but most leaches with the water out of the bottom of the soil profile. When water evaporates at the soil surface, or from leaves, it is pure, containing no salt, so evapotranspiration concentrates the salts in the soil. If more salt is applied in the irrigation water than is leached or taken off in harvested plants, the soil becomes more saline and eventually will cease to support agricultural production. Thousands of acres have been lost from production in this way, and production has been drastically reduced on tens of thousands of additional acres.

SOIL SALINITY AND ELECTRICAL CONDUCTIVITY

Soil salinity has been measured using electrical conductivity (EC) for more than 100 years. It is common knowledge that salty water conducts electricity. Whitney and Means (1897) made use of that fact to measure the concentration of salt in soil. Early methods made measurements directly on a soil paste, but the influence of the soil in the paste on the measurement was not fully understood until recently, leading to uncertainty in the measurements. By about 1940, the accepted method for determining soil salinity was to make a saturated paste by a specified procedure, extract solution from the paste, and measure the electrical conductivity of the solution (Richards, 1954). The measurement is referred to as the electrical conductivity of the saturation extract. These values were then correlated with crop response.

Richards (1954) defined four soil salinity classes, as shown in Table 1. Crops suitable for these classes are also listed by Richards, but a much more extensive list is given by Rhoades and Lovejoy (1990). For example, “Bean” is listed as a sensitive crop. It can only be grown without yield damage in soils with EC below 2 dS/m. Barley is a tolerant crop. It can be grown without much yield reduction in any soil up to EC of 16 dS/m.

USDA Class	Conductivity Range dS/m	Salt in Soil g/100g	Osmotic Potential kPa	Crop Salt Tolerance	Example Crop
A	0-2	0-0.13	0 to -70	Sensitive	Bean
B	2-4	0.13-0.26	-70 to -140	Moderately sensitive	Corn
C	4-8	0.26-0.51	-140 to -280	Moderately tolerant	Wheat
D	8-16	-0.51-1.02	-280 to 560	Tolerant	Barley

Table 1. Salinity classes for soils

Two other columns are shown in the table. The “Salt in soil” column shows how much salt is required to salinize a soil. In terms of the total soil mass, only a small percentage change is needed to make a big difference in salinity, but this would still represent a large addition of fertilizer. A 200 kg/ha addition of fertilizer would represent a fairly high rate. If this were incorporated into the top 15 cm of soil, it would represent

$$200 \frac{\text{kg}_{\text{fert}}}{\text{ha}} \times \frac{1\text{ha}}{10^4\text{m}^2} \times \frac{1}{0.15\text{m}} \times \frac{1\text{m}^3}{1.3 \times 10^3\text{kg}_{\text{soil}}} \times 100 = 0.01\%$$

This wouldn't cause much change in soil salt percentage.

The other column shows the osmotic potential of the saturation extract. To give some reference for this number, remember that the nominal permanent wilt water

potential of soil is -1500 kPa. Osmotic potentials of plant leaves vary widely depending on species, but -1500 kPa is a kind of median value. The values in the table may seem small compared to the [permanent wilt](#) (PW) value, but remember that these are values at saturation. When a soil is saturated, water quickly drains to a “[drained upper limit](#)” (UL) water content which is around half the saturation value. The useful water storage of the soil is between the UL and the PW or lower limit water content, which, again, is about half the UL. The concentration of salts at the UL is about the same as at saturation because the water drained away, but the water loss between the UL and PW is typically by evapotranspiration so little or no salts are lost. The concentration at the lower limit is, therefore, twice that shown in Table 1, which is significant compared to the permanent wilt water potential. Likewise, the [osmotic potential](#) of the soil solution after fertilizing with 200 kg/ka and mixing wouldn't change much, but the same amount of fertilizer concentrated in a band near seed would have a much larger effect.

MEASURING ELECTRICAL CONDUCTIVITY OF THE SOIL SOLUTION

As mentioned above, the earliest measurements of solution conductivity were made on soil samples, but it was found to be more reliable to extract the soil solution and make the measurements on it. When values for unsaturated soils are needed, those are calculated based on the saturation numbers and conjecture about how the soil dried to its present state. Obviously, a direct measurement of the soil solution conductivity would be better if it could be made reliably. Two approaches have been made to this measurement. The first uses platinum electrodes embedded in ceramic with a bubbling pressure of 15 bars. Over the plant growth range, the ceramic remains saturated, even though the soil is not saturated, allowing a measurement of the solution in the ceramic. As long as there is adequate exchange between the ceramic and the soil solution, this measurement will be the EC of the soil solution or pore water EC. The other method measures the conductivity of the bulk soil and then uses empirical or theoretical equations to determine the pore water EC. The METER 5TE soil moisture sensor uses the second method. It requires no exchange of salt between soil and sensor and is, therefore, more likely to indicate the actual solution electrical conductivity. The following analysis shows one of several methods for determining the electrical conductivity of the saturation extract from measurements of the bulk soil electrical conductivity.

Mualem and Friedman (1991) proposed a model based on soil hydraulic properties. It assumes two parallel conduction paths, one along the surface of soil particles and the other through the soil water. The model is

$$\sigma_b = \sigma_s + \sigma_w \frac{\theta^{n+2}}{\theta_s}$$

Equation 1

Here σ_b is the bulk conductivity, which is measured by the probe; σ_s is the bulk surface conductivity; σ_w is the conductivity of the pore water; θ is the volumetric water content; θ_s is the saturation water content of the soil; and n is an empirical parameter with a suggested value around 0.5. If, for the moment, we ignore surface conductivity and use Equation 1 to compute the electrical conductivity of a saturated paste (assuming $n = 0.5$ and $\theta_s = 0.5$) we obtain $\sigma_b = 0.35 \sigma_w$. Obviously, if no soil were there, the bulk reading would equal the electrical conductivity of the water, but when soil is there the bulk conductivity is about a third of the solution conductivity. This happens because soil particles take up some of the space, decreasing the cross section for ion flow and increasing the distance ions must travel (around particles) to move from one electrode of the probe to the other. In unsaturated soil, these same concepts apply, but here both soil particles and empty pores interfere with ion transport, so the bulk conductivity becomes an even smaller fraction of pore water conductivity. Our interest, of course, is in the pore water conductivity. Inverting Equation 1 we obtain

$$\sigma_w = \frac{\sigma_b - \sigma_s}{\theta^{n+2} / \theta_s}$$

Equation 2

In order to know pore water conductivity from measurements in the soil, we must also know the soil water content, the saturation water content, and the surface conductivity. The 5TE soil moisture sensor measures the water content. The saturation water content can be computed from the bulk density of the soil

$$\theta_s = 1 - \rho_b / \rho_s$$

Equation 3

Where ρ_b is the soil bulk density and ρ_s is the density of the solid particles, which, in mineral soils, is taken to be around 2.65 Mg/m³. The surface conductivity is assumed to be zero for coarse-textured soil. Therefore, using the 5TE can allow us to quantify pore water EC through the use of the above assumptions. This knowledge has the potential to be a very useful tool in fertilizer scheduling.

TEMPERATURE DEPENDENCE OF ELECTRICAL CONDUCTIVITY

Electrical conductivity, of solutions or soils, changes by about 2% per Celsius degree. Because of this, measurements must be corrected for temperature in order to be useful. Richards (1954) provides a table for correcting the readings taken at any temperature to readings at 25 °C. The following polynomial summarizes the table:

$$\sigma_{(25)} = \sigma(-6.04 \times 10^{-6} T^3 + 8.511 \times 10^{-4} T^2 - 0.0515T + 1.849)$$

where t is the Celsius temperature. This equation is programmed into the 5TE, so temperature corrections are automatic.

UNITS OF ELECTRICAL CONDUCTIVITY

The SI unit for electrical conductance is the Siemen (S), so electrical conductivity has units of S/m. Units used in older literature are mho/cm (mho is reciprocal ohm), which have the same value as S/cm. Soil electrical conductivities were typically reported in mmho/cm so 1 mmho/cm equals 1 mS/cm. Since SI discourages the use of submultiples in the denominator, this unit is changed to deciSiemen per meter (dS/m), which is numerically the same as mmho/cm or mS/cm. Occasionally EC is reported as mS/m or μ S/m. 1 dS/m is 100 mS/m or $10^5 \mu$ S/m.

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