

# Soil Sodicity

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## ABSTRACT

Soil sodicity refers to the amount of sodium held on soil cation exchange sites. It is typically expressed either as the percentage of the soil cation exchange capacity filled with sodium ions (exchangeable sodium percentage or ESP), or as a ratio comparing exchangeable sodium to exchangeable calcium plus magnesium (sodium adsorption ratio or SAR). Our primary interest in soil sodium is its impact on soil structure. Sodium, like all soil cations, can flocculate clay particles if present in adequate quantities, but sodium is a very weak flocculator. As a consequence, soils affected by high levels of sodium are likely to be poorly aggregated or to have weak, unstable aggregates. These soils often exhibit slow water infiltration and poor internal drainage, as well as elevated pH. We will explore the relationship between soil salinity, soil sodicity, and physical soil attributes as well as management options for dealing with sodium-affected soils.

## INTRODUCTION

Soil sodium is of interest primarily because of its impact on soil structure. Soil aggregates are conglomerations of sand, silt, clay, and organic matter particles. Aggregate size, shape, and strength comprise what is referred to as soil structure. Aggregates are larger than primary soil particles and the relatively large pores between aggregates (inter-aggregate pores; open spaces in the soil volume) are critical for water infiltration into soils, root penetration, soil drainage, and soil aeration. Aggregation is to some extent a *manageable* soil physical property, unlike soil texture for example. Inter-aggregate pores are large relative to the pores within aggregates which may be too small for effective water movement, and may be too small even for root hairs to enter. In all but the sandiest soils, which have large pores between sand grains, good aggregate structure is critical for maintaining conditions conducive to plant growth. Good soil structure provides open pathways that roots grow through and large pores that transmit water and, when empty, supply plant roots with essential oxygen.

## PRINCIPLES

In most temperate-region soils, clay particles carry a negative electrical charge. Negatively-charged particles repel one another due to electrostatic repulsion forces, but soil particles can be bound together into aggregates by positively charged molecules (cations). The process of aggregate formation, flocculation, is promoted by the presence of adequate levels of flocculating cations. The dominant soil cations in medium to high pH soils are the monovalent cations (one positive charge per molecule) sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ), and the divalent cations (two charges per molecule) magnesium ( $\text{Mg}^{2+}$ ) and calcium ( $\text{Ca}^{2+}$ ). In acidic soils the trivalent aluminum cation ( $\text{Al}^{3+}$ ) is present. Of these cations  $\text{Al}^{3+}$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$  are effective flocculators;  $\text{Na}^+$  and  $\text{K}^+$  are not. The relative amounts of “weak” and “strong” flocculators can give an indication of

how likely a soil is to flocculate or to remain flocculated. Exchangeable Sodium Percentage (ESP) or Sodium Adsorption Ratio (SAR), can be used for this purpose:

$$ESP = 100 \times \left( \frac{Na^+}{\text{Cation Exchange Capacity}} \right)$$

$$SAR = \frac{Na^+}{\sqrt{\left( \frac{Ca^{2+} + Mg^{2+}}{2} \right)}}$$

where  $Na^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$  concentrations and Cation Exchange Capacity are expressed in units of charge (cmol<sub>c</sub>/kg of soil).

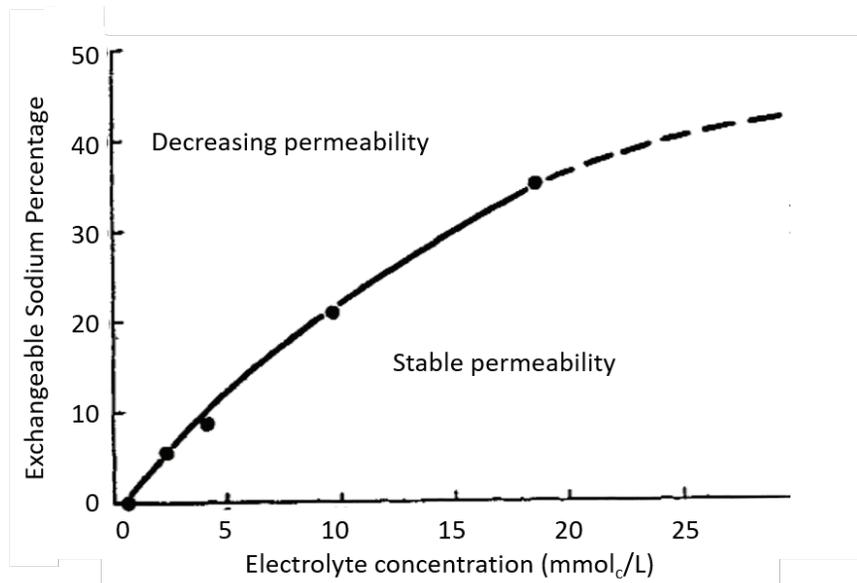
Rengasamy and Marchuk (2011) proposed the Cation Ratio of Structural Stability (CROSS) that more precisely predicts the impacts of soil cations than the SAR calculation. This was later modified (CROSS<sub>opt</sub>) by Oster et al. (2106). CROSS adds potassium to the SAR calculation and modifies the relative impacts of individual ions.

$$CROSS_{opt} = \frac{(Na + 0.335K)}{\sqrt{\left( \frac{Ca + 0.0758Mg}{2} \right)}}$$

Soil particle flocculation is promoted not only by a high proportion of effective flocculating cations, but also by a high concentration of ions in general, which is denoted by a high salt content. Soil salt levels are measured and expressed as Electrical Conductivity (EC) in units of deciSiemens per meter (dS/m). High EC indicates the presence of large quantities of salt ions. Soil flocculation is promoted in high EC soils.

To fully understand soil aggregation or dispersion (lack of aggregation), we must simultaneously consider both soil sodicity and soil salinity. Figure 1 shows the relative effects of ESP (on the vertical axis) and salinity level expressed as mmol<sub>c</sub> of salts (on the horizontal axis) on soil aggregate stability as reflected in water infiltration rate. If soil ESP is low, meaning that the Na concentration is relatively low, then the soil likely has stable aggregates and accepts water readily. On the other hand, aggregates in soil with high levels of salinity can remain stable even in soil with a high sodium levels. Those soils with a combination of low sodium and low salinity are most subject to loss of aggregation, or dispersion, which can result in declining permeability. Ultimately, both sodicity and salinity profoundly affect extent and stability of soil aggregates. However, high levels of soil salinity that improve flocculation may not provide a good environment for growth of salt-sensitive plants because the level of salinity needed to flocculate sodic soils may be too high for optimum plant growth. Conditions that promote good soil physical properties may not always promote plant growth.

Sodium-impacted soils typically have pH levels higher than other soils. Whereas the pH of calcium carbonate containing soils is generally no higher than approximately 8.5, the presence of sodium carbonate minerals can raise soil pH above 9.0. The indirect effect of extremely alkaline soils is primarily related to nutrient availability limitations.



**Figure 1.** Effects of ESP and Electrolyte Concentration on Soil Permeability (Quirk and Schofield, 1955).

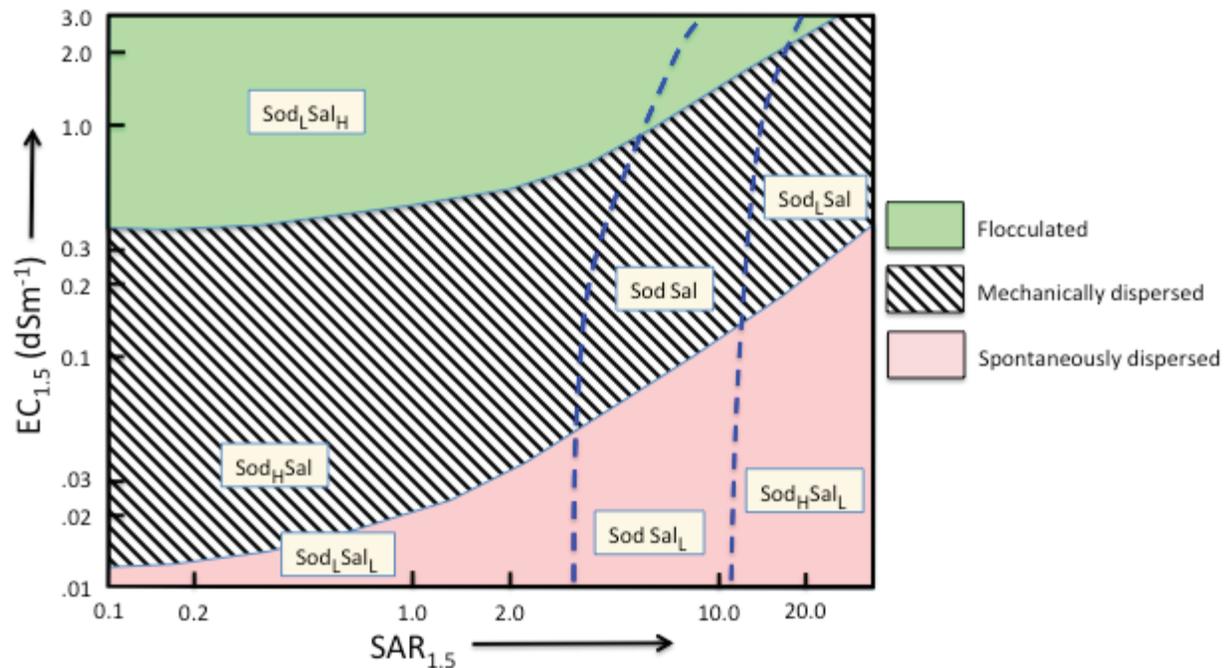
### PROPERTIES OF SODIUM-AFFECTED SOILS

The most noticeable properties of sodium-impacted soils are slowed water infiltration and poor drainage. In these soils, irrigation water and rainfall soak into the soil slowly, or pond and run off the soil surface. Soil profile water will drain slowly, so salts added in irrigation water or from other sources accumulate, elevating soil salinity levels. Soil salinity may reach phytotoxic levels, resulting in reduced plant growth and crop yields. When sodium-affected soils dry, they may form surface hard crusts that can impede seedling emergence. For these reasons, it is important to measure both soil salinity and soil sodium. Additionally, thorough evaluation requires irrigation water analyses because this water is typically the major source of both soil sodium and salts in irrigated soils. Over time, characteristics of irrigated soils will reflect the properties of the irrigation water. At minimum, irrigation water analysis should include EC, SAR or CROSS, carbonate, and bicarbonate.

According to USDA classification a soil is classified as saline, meaning it contains excess salt, if the EC is greater than 4 dS/m. Soil is classified as sodic if the ESP is greater than 15% or if SAR is greater than 13. A saline-sodic soil has an EC greater than 4 dS/m and an ESP greater than 15% or an SAR greater than 13. Soil aggregation and water infiltration of sodic soil are expected to be most adversely affected in sodic soils because of their relatively high levels of sodium and low levels of salinity (low EC). Sodic soils are extremely difficult to manage and are, fortunately, rare. However, soils not classified as sodic (i.e. ESP < 15 or SAR < 13) also can be negatively affected by sodium. We can properly refer to these as sodium-affected soils even though they are not “sodic” according to USDA specifications. The precise ESP or SAR value at which soil structure is degraded is dependent on soil salinity level, as we have seen, and also soil texture and mineralogical composition. For example, a very sandy soil may contain enough large pores that water moves through the soil profile, even in the presence of large amounts of sodium.

A classification scheme presented by Sumner et al. (1998) has greater resolution than the USDA classification, and clarifies the relationship between salinity and sodicity with respect to soil structural stability (Figure 2). Note that the method of measuring sodicity and salinity are

different than those typically used in the United States (they are measured in a 1:5 soil:water extract rather than in a saturated paste extract). Although the actual values are not directly transferable, the concepts and relationships are instructive as the figure shows how salinity and sodicity impact strength and stability of aggregation.



**Figure 2.** Proposed scheme for description of Na-affected soils in terms of physical behavior (dispersibility) and sodium (Sod) and salinity (Sal) classes (Sumner et al., 1998).

## MONITORING AND MANAGEMENT

It is useful to consider sodium impact functionally by looking at how sodium affects physical properties of soil, in addition to quantitative measurements. Soil managers can monitor and track soil EC and ESP (or SAR or CROSS) to look for long-term trends. Salinity and sodicity change slowly, so it's important to conduct routine soil sampling and analysis and to track changes occurring over multiple years that can indicate increasing salinity or sodicity. Changes that may identify declining soil aggregate stability also can be detected by watching for slowing water infiltration rates over time.

Excess soil sodium can be addressed by increasing the amount of soluble soil calcium. Elevated soluble calcium mitigates the negative effects of sodium by encouraging flocculation of clay particles, and stabilizing soil structure. There are two alternatives for increasing soluble soil calcium: solubilize calcium already present in the soil, or add supplemental calcium.

The first option, solubilizing existing soil calcium, can work only if the soil contains calcium carbonate ( $\text{CaCO}_3$ ) minerals, soils known as calcareous. Soil carbonates are identified on soil test reports as the level of "free lime." One also can test for the presence of carbonates by putting a drop of dilute acid on them and observing whether or not the soil effervesces or bubbles as the carbonate reacts with the acid to produce carbon dioxide gas (Figure 3). In soils with "medium" or "high" or "very high" free lime or reacting vigorously when combined with acid, an acid can be applied to dissolve soil calcium carbonate. As the acid dissolves calcium carbonate the released calcium reacts with soil clays, acting as a flocculant. The most commonly used acid is sulfuric acid

( $H_2SO_4$ ), although other acids can perform the same function. Sulfurous acid ( $H_2SO_3$ ) can be produced on-site in agricultural fields by combustion of elemental sulfur in a “sulfur burner.” Additionally, acid-forming materials such as elemental sulfur can be used. Elemental sulfur is converted to sulfuric acid by sulfur-oxidizing soil bacteria, producing sulfuric acid. Sulfur conversion to sulfuric acid is a biological process, and requires several weeks to months to take place, depending on soil conditions. Acids and acid-forming materials will only be effective in calcareous soils.



**Figure 3.** Test for the presence of soil carbonates by adding a drop of acid. Calcareous soils will produce carbon dioxide bubbles.

Alternatively, calcium-bearing minerals can be amended to soil as a source of soluble calcium. Gypsum ( $CaSO_4 \cdot 2H_2O$ ) is the most common. Closely related anhydrite ( $CaSO_4$ ) is also used. Chemically, these two minerals are very similar, the difference being that calcium sulfate anhydrite does not contain water. Consequently, calcium sulfate anhydrite contains more calcium on a weight basis than gypsum (anhydrite contains 29.4% Ca; gypsum 23.2% Ca). Both of these minerals are mined, and then ground into a powder for use as soil additives. Additionally, by-product gypsum materials, waste products of phosphate fertilizer production (phospho-gypsum) or from power plant stack scrubbers (flue gas desulfurization gypsum), are also used.

Calcium carbonate or limestone is another calcium mineral used as a soil amendment and is referred to as lime or agricultural lime. The main use of lime is to raise soil pH (to reduce acidity). It's not an appropriate source of calcium in high pH arid-region soils because it is only soluble in acidic soils.

## SUMMARY

Dissolved or exchangeable sodium can degrade soil physical properties by affecting soil flocculation/dispersion. Soil cations vary in their ability to flocculate soils, and sodium is the weakest flocculator of the common soil cations. Irrigation water is the primary source of salts and sodium in irrigated soils. High levels of sodium and, to a lesser degree potassium, in conjunction

with low levels of calcium and magnesium, weakens and degrades soil structure. This can impede water movement into and within the soil profile and result in accumulation of soil salts.

Irrigation water and soil sodium should be monitored, and mitigating strategies adopted if sodium inputs threaten soil structural stability. Available soil treatments include various methods of solubilizing existing soil carbonate minerals or adding soluble calcium forms.

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