Chapter 1

Origin and Nature of Saline and Alkali Soils

The soils under consideration in this handbook owe their distinctive character to the fact that they contain excessive concentrations of either soluble salts or exchangeable sodium, or both. For agricultural purposes, such soils are regarded as a class of problem soils that requires special remedial measures and management practices. Soluble salts produce harmful effects to plants by increasing the salt content of the soil solution and by increasing the degree of saturation of the exchange materials in the soil with exchangeable sodium. The latter effect occurs when the soluble constituents consist largely of sodium salts and is of a more permanent nature than the salt content of the soil solution, since exchangeable sodium usually persists after the soluble salts are removed.

In discussing these problem soils it is convenient to use terms that refer specifically to the two principal causes of the problem. "Saline soil," as used in this handbook, refers to a soil that contains sufficient soluble salts to impair its productivity. Similarly, alkali soils can be defined in terms of productivity as influenced by exchangeable sodium. In accordance with this usage, alkali soils may or may not contain excess soluble salts. Probably the most common problem involves soils that contain an excess of both soluble salts and exchangeable sodium, and, in agreement with the terminology of De Sigmond (1938),[1] these soils will be referred to as saline-alkali soils.

The salt content of soils above which plant growth is affected depends upon several factors, among which are the texture of soil, the distribution of salt in the profile, the composition of the salt, and the species of plant. Several arbitrary limits for salinity have been suggested for distinguishing saline from nonsaline soils. Kearney and Scofield (1936), in discussing the choice of crops for saline lands, considered that plants begin to be adversely affected as the salt content of the soil exceeds 0.1 percent. De Sigmond (1938) was in agreement with this limit. In the report of the United States National Resources Planning Board (1942, pp. 263-334) relative to the Pecos River investigation, Scofield considered a soil to be saline if the solution extracted from a saturated soil paste had an electrical conductivity value of 4 mmhos/cm. or more. The electrical conductivity of the saturation extract was adopted by the Salinity Laboratory as the preferred scale for general use in estimating soil salinity. The Soil Survey Staff (1951) of the United States Department of Agriculture now uses either this method or the earlier method based on the electrical resistance of a sample of soil paste, the latter reading being converted to the dry-weight percentage of soluble salt in the soil.

The decision regarding what level of exchangeable sodium in the soil constitutes an excessive degree of saturation is complicated by the fact that there is no sharp change in the properties of the soil as the degree of saturation with exchangeable sodium is increased. In the past an exchangeable-sodium-percentage of 15 has been used at the Laboratory as a boundary limit between nonalkali and alkali soils. Insufficient data and experience are available to justify a change, but this limit must be regarded as somewhat arbitrary and tentative. In some cases, for example, 2 or 3 milliequivalents of exchangeable sodium per 100 gm. of soil has equal or even greater usefulness as a critical limit.

There has been uncertainty in the past regarding the effect of exchangeable potassium on the physical properties of soils and if, as De Sigmond (1928) and Magistad (1945) have proposed, exchangeable sodium and potassium should be considered as additive in defining alkali soils. It has been observed in several instances that alkali soils high in exchangeable potassium have better physical properties and are more readily reclaimable than other alkali soils containing similar amounts of exchangeable sodium but low amounts of exchangeable potassium. The view that exchangeable potassium has only a slight or no adverse effect upon the physical properties of soils is supported by the results of measurements made recently at the Laboratory[2] on samples of seven soils adjusted to various levels of exchangeable sodium and exchangeable potassium (fig. 1).

The magnitude of the air: water permeability ratio is a measure of the extent to which soil structure deteriorates when water is applied, a high ratio indicating a high degree of deterioration. The data for

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[1] References to Literature Cited (p. 148) are herein indicated by the name of the author (or authors) followed by the year of publication.

[2] Unpublished data by R. C. Reeve, C. A. Bower, R. H. Brooks, and F. B. Gschwend.

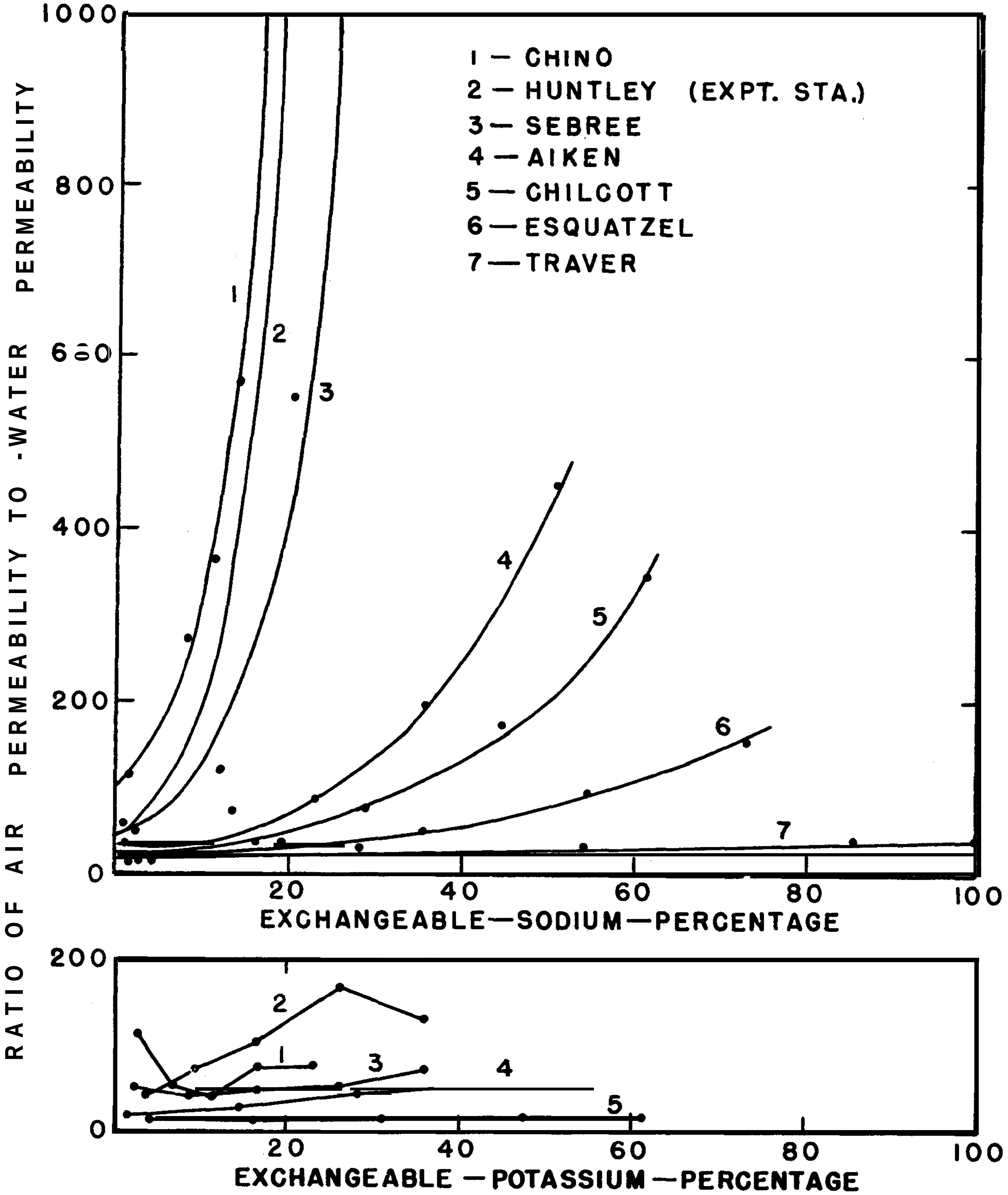

Figure 1.—Relative effect of exchangeable sodium and exchangeable potassium on the ratio of the air permeability to the water permeability of soils.

two soils are not plotted in the graph showing the effect of the exchangeable-potassium-percentage, because they nearly coincide with the lower curve. In general, the increase in ratio with increase in exchangeable sodium is directly related to the total specific surface of the soils.

Improvements are being made in methods of appraising both the susceptibility and the status of soils with respect to the injurious effects of exchangeable sodium. For these reasons, both the terminology and the classification limits for alkali soils must be regarded as being in a transitional stage.

Sources of Soluble Salts

The soluble salts that occur in soils consist mostly of various proportions of the cations sodium, calcium, and magnesium, and the anions chloride and sulfate. Constituents that ordinarily occur only in minor amounts are the cation potassium and the anions bicarbonate, carbonate, and nitrate. The original and, to some extent, the direct source of all the salt constituents are the primary minerals found in soils and in the exposed rocks of the earth's crust. Clarke (1924) has estimated that the average chlorine and sulfur content of the earth's crust is 0.05 and 0.06 percent, respectively, while sodium, calcium, and magnesium each occur to the extent of 2 or 3 percent. During the process of chemical weathering, which involves hydrolysis, hydration, solution, oxidation, and carbonation, these constituents are gradually released and made soluble.

Bicarbonate ions form as a result of the solution of carbon dioxide in water. The carbon dioxide may be of atmospheric or biological origin. Water containing carbon dioxide is a particularly active chemical weathering agent that releases appreciable quantities of the cation constituents as the bicarbonates. Carbonate and bicarbonate ions are interrelated, the relative amounts of each present being a function of the pH value of the solution. Appreciable amounts of carbonate ions can be present only at pH values of 9.5 or higher.

While the above-mentioned salt constituents are of most importance in saline soils, there are places, as in parts of Colorado, Utah, and Washington, where high concentrations of nitrate are found. Various theories (Kelley, 1951) have been proposed to explain the origin of excessive nitrate salts in soils. Boron, owing to its marked toxicity to plants when present even in low concentrations, also deserves mention (Eaton and Wilcox, 1939). The principal source of this element is the mineral tourmaline, which is a rather widespread but minor constituent of primary rocks.

Although weathering of primary minerals is the indirect source of nearly all soluble salts, there are probably few instances where sufficient salts have accumulated in place from this source alone to form a saline soil. Saline soils usually occur in areas that receive salts from other locations, and water is the primary carrier. The ocean may be the source of salts as in soils where the parent material consists of marine deposits that were laid down during earlier geologic periods and have since been uplifted. The Mancos shales occurring in Colorado, Wyoming, and Utah are typical examples of saline marine deposits. The ocean is also the source of the salts in low-lying soils along the margin of seacoasts. Sometimes salt is moved inland through the transportation of spray by winds and is called cyclic salt (Teakle, 1937) . More commonly, however, the direct source of salts is surface and ground waters. All of these waters contain dissolved salts, the concentration depending upon the salt content of the soil and geologic materials with which the water has been in contact. Waters act as sources of salts when used for irrigation. They may also add salts to soils under natural conditions, as when they flood low-lying land or when ground water rises close to the soil surface.

Salinization of Soils

Saline soils occur for the most part in regions of arid or semiarid climate. Under humid conditions the soluble salts originally present in soil materials and those formed by the weathering of minerals generally are carried downward into the ground water and are' transported ultimately by streams to the oceans. Saline soils are, therefore, practically nonexistent in humid regions, except when the soil has been subjected to sea water in river deltas and other low-lying lands near the sea. In arid regions leaching and transportation of soluble salts to the ocean is not so complete as in humid regions. Leaching is usually local in nature, and soluble salts may not be transported far. This occurs not only because there is less rainfall available to leach and transport the salts but also because of the high evaporation rates characteristic of arid climates, which tend further to concentrate the salts in soils and in surface waters.

Restricted drainage is a factor that usually contributes to the salinization of soils and may involve the presence of a high ground-water table or low permeability of the soil. The high ground-water table is often related to topography. Owing to the low rainfall in arid regions, surface drainageways may be poorly developed. As a consequence, there are drainage basins that have no outlet to permanent streams. The drainage of salt-bearing waters away from the higher lands of the basin may raise the ground-water level to the soil surface on the lower lands, may cause temporary flooding, or may form permanent salty lakes. Under such conditions upward movement of saline ground water or evaporation of surface water results in the formation of saline soil. The extent of saline areas thus formed may vary from a few acres to hundreds of square miles. Many of the saline soils in the Great Basin were formed in this manner. Similar areas occur throughout the Western States. They are often referred to as playas or dry lakes.

Low permeability of the soil causes poor drainage by impeding the downward movement of water. Low permeability may be the result of an unfavorable soil texture or structure or the presence of indurated layers. The latter may consist of a claypan, a caliche layer, or a silica hardpan. De Sigmond (1924) considered the presence of an impermeable soil layer essential for the formation of the saline soils found in Hungary.

The salinity problem of principal economic importance arises when previously nonsaline soil becomes saline as the result of irrigation. Such soils are often located in valleys adjacent to streams, and, because of the ease with which they can be irrigated, the more level areas are usually selected for cultivation. While such soils may be well drained and nonsaline under natural conditions, the drainage may not be adequate for irrigation. When bringing new lands under irrigation, farmers have frequently failed to recognize the need for establishing artificial drains to care for the additional water and soluble salts. As a result, the ground-water table may rise from a considerable depth to within a few feet of the soil surface in a few years. During the early development of irrigation projects, water is frequently plentiful and there is a tendency to use it in excess. This hastens the rise of the water table. Waters used for irrigation may contain from 0.1 to as much as 5 tons of salt per acre-foot of water, and the annual application of water may amount to 5 feet or more. Thus, considerable quantities of soluble salts may be added to irrigated soils over relatively short periods of time. When the water table rises to within 5 or 6 feet of the soil surface, ground water moves upward into the root zone and to the soil surface. Under such conditions, ground water, as well as irrigation water, contributes to the salinization of the soil.

Alkalization or Accumulation of Exchangeable Sodium in Soils

Soil particles adsorb and retain cations on their surfaces. Cation adsorption occurs as a consequence of the electrical charges at the surface of the soil particles. While adsorbed cations are combined chemically with the soil particles, they may be replaced by other cations that occur in the soil solution. The reaction whereby a cation in solution replaces an adsorbed cation is called cation exchange. Sodium, calcium, and magnesium cations are always readily exchangeable. Other cations, like potassium and ammonium, may be held at certain positions on the particles in some soils so that they are exchanged with great difficulty and, hence, are said to be fixed.

Cation adsorption, being a surface phenomenon, is identified mainly with the fine silt, clay, and organic matter fractions of soils. Many different kinds of minerals and organic materials occurring in soils have exchange properties and together are referred to as the exchange complex. The capacity of a soil to adsorb and exchange cations can be measured and expressed in chemical equivalents and is called the cation-exchange-capacity. It is commonly expressed in milliequivalents per 100 gm. of soil. Various chemical and physical factors interact to make the measured value depend somewhat on the method of determination, but, nevertheless, the cation-exchange-capacity is a reasonably definite soil property that has considerable practical significance. In view of the fact that the adsorbed cations can interchange freely with adjacent cations in the soil solution, it is to be expected that the proportion of the various cations on the exchange complex will be related to their concentrations in the soil solution.

Calcium and magnesium are the principal cations found in the soil solution and on the exchange complex of normal soils in arid regions. When excess soluble salts accumulate in these soils, sodium frequently becomes the dominant cation in the soil solution. Thus, sodium may be the predominant cation to which the soil has been subjected, or it may become dominant in the soil solution, owing to the precipitation of calcium and magnesium compounds. As the soil solution becomes concentrated through evaporation or water absorption by plants, the solubility limits of calcium sulfate, calcium carbonate, and magnesium carbonate are often exceeded, in which case they are precipitated with a corresponding increase in the relative proportion of sodium. Under such conditions, a part of the original exchangeable calcium and magnesium is replaced by sodium.

From a practical viewpoint, it is fortunate that the calcium and magnesium cations in the soil solution are more strongly adsorbed by the exchange complex than sodium. At equivalent solution concentrations, the amounts of calcium and magnesium adsorbed are several times that of sodium. In general, half or more of the soluble cations must be sodium before significant amounts are adsorbed by the exchange complex. In some saline soil solutions, however, practically all of the cations are sodium, and in these sodium is the predominant adsorbed cation.

Characteristics of Saline and Alkali Soils

The term “soil” is used in several senses by agriculturists. In one sense a soil is considered to be a three-dimensional piece of landscape having shape, area, and depth (Soil Survey, 1951). The concept of a soil as a profile having depth but not necessarily shape or area is also a common use of the term. In another sense, often used in this handbook, the term is applied to samples representing layers or points in the profile. Saline and alkali soils are defined and diagnosed on the basis of determinations made on soil samples, and the significance of information thus obtained contributes substantially to scientific agriculture. The extension and harmonization of these definitions to the problems and purposes of soil survey and soil classification have not been attempted, because it lies somewhat beyond the scope of the present work.

To facilitate and clarify this discussion, the problem soils under consideration have been separated into three groups : Saline, saline-alkali, and nonsaline-alkali soils.

Saline Soils

Saline is used in connection with soils for which the conductivity of the saturation extract is more than 4 mmhos/cm. at 25” C. and the exchangeable-sodium-percentage is less than 15. Ordinarily, the pH is less than 8.5. These soils correspond to Hilgard’s (1906) “white alkali” soils and to the “Solonchaks” of the Russian soil scientists. When adequate drainage is established, the excessive soluble salts may be removed by leaching and they again become normal soils.

Saline soils are often recognized by the presence of white crusts of salts on the surface. Soil salinity may occur in soils having distinctly developed profile characteristics or in undifferentiated soil material such as alluvium.

The chemical characteristics of soils classed as saline are mainly determined by the kinds and amounts of salts present. The amount of soluble salts present controls the osmotic pressure of the soil solution. Sodium seldom comprises more than half of the soluble cations and hence is not adsorbed to any significant extent. The relative amounts of calcium and magnesium present in the soil solution and on the exchange complex may vary considerably. Soluble and exchangeable potassium are ordinarily minor constituents, but occasionally they may he major constituents. The chief anions are chloride, sulfate, and sometimes nitrate. Small amounts of bicarbonate may occur, but soluble carbonates are almost invariably absent. In addition to the readily soluble salts, saline soils may contain salts of low solubility, such as calcium sulfate (gypsum) and calcium and magnesium carbonates (lime) .

Owing to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils generally are flocculated; and, as a consequence, the permeability is equal to or higher than that of similar nonsaline soils.

Saline-Alkali Soils

Saline-alkali is applied to soils for which the conductivity of the saturation extract is greater than 4 mmhos/cm. at 25” C. and the exchangeable-sodium-percentage is greater than 15. These soils form as a result of the combined processes of salinization and alkalization. As long as excess salts are present, the appearance and properties of these soils are generally similar to those of saline soils. Under conditions of excess salts, the pH readings are seldom higher than 8.5 and the particles remain flocculated. If the excess soluble salts are leached downward, the properties of these soils may change markedly and become similar to those of nonsaline-alkali soils. As the concentration of the salts in the soil solution is lowered, some of the exchangeable sodium hydrolyzes and forms sodium hydroxide. This may change to sodium carbonate upon reaction with carbon dioxide absorbed from the atmosphere. In any event, upon leaching, the soil may become strongly alkaline (pH readings above 8.5) , the particles disperse, and the soil becomes unfavorable for the entry and movement of water and for tillage. Although the return of the soluble salts may lower the pH reading and restore the particles to a flocculated condition, the management of saline-alkali soils continues to be a problem until the excess salts and exchangeable sodium are removed from the root zone and a favorable physical condition of the soil is reestablished.

Saline-alkali soils sometimes contain gypsum. When such soils are leached, calcium dissolves and the replacement of exchangeable sodium by calcium takes place concurrently with the removal of excess salts.

Nonsaline-Alkali Soils

Nonsaline-alkali is applied to soils for which the exchangeable-sodium-percentage is greater than 15 and the conductivity of the saturation extract is less than 4 mmhos/cm. at 25” C. The pH readings usually range between 8.5 and 10. These soils correspond to Hilgard’s “black alkali” soils and in some cases to “Solonetz,” as the latter term is used by the Russians. They frequently occur in semiarid and arid regions in small irregular areas, which are often referred to as “slick spots.” Except when gypsum is present in the soil or the irrigation water, the drainage and leaching of saline-alkali soils leads to the formation of nonsaline-alkali soils. As mentioned in the discussion of saline-alkali soils, the removal of excess salts in such soils tends to increase the rate of hydrolysis of the exchangeable sodium and often causes a rise of the pH reading of the soil. Dispersed and dissolved organic matter present in the soil solution of highly alkaline soils may be deposited on the soil surface by evaporation, thus causing darkening and giving rise to the term “black alkali.”

If allowed sufficient time, nonsaline-alkali soils develop characteristic morphological features. Because partially sodium-saturated clay is highly dispersed, it may be transported downward through the soil and accumulate at lower levels. As a result, a few inches of the surface soil may be relatively coarse in texture and friable; but below, where the clay accumulates, the soil may develop a dense layer of low permeability that may have a columnar or prismatic structure. Commonly, however, alkali conditions develop in such soils as a result of irrigation. In such cases, sufficient time usually has not elapsed for the development of the typical columnar structure, but the soil has low permeability and is difficult to till.

The exchangeable sodium present in nonsaline-alkali soil may have a marked influence on the physical and chemical properties. As the proportion of exchangeable sodium increases, the soil tends to become more dispersed. The pH reading may increase, sometimes becoming as high as 10. The soil solution of nonsaline-alkali soils, although relatively low in soluble salts, has a composition that differs considerably from that of normal and saline soils. While the anions present consist mostly of chloride, sulfate, and bicarbonate, small amounts of carbonate often occur. At high pH readings and in the presence of carbonate ions, calcium and magnesium are precipitated; hence, the soil solutions of nonsaline-alkali soils usually contain only small amounts of these cations, sodium being the predominant one. Large quantities of exchangeable and soluble potassium may occur in some of these soils.

The effect of excessive exchangeable potassium on soil properties has not been sufficiently studied.

Nonsaline-alkali soils in some areas of western United States have exchangeable-sodium-percentages considerably above 15, and yet the pH reading, especially in the surface soil, may be as low as 6. These soils have been referred to by De Sigmond (1938) as degraded alkali soils. They occur only in the absence of lime, and the low pH reading is the result of exchangeable hydrogen. The physical properties, however, are dominated by the exchangeable sodium and are typically those of a nonsaline-alkali soil.