Reclamation of salt-affected soil

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19 Reclamation of Salt-Affected Soils

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I. INTRODUCTION

Reclamation of salt-affected soils through tillage, water, crop, and amendment practices is an increasingly important tool for improving crop productivity in many areas of the world. Traditionally, reclamation has been driven by the need to turn marginally arable lands to agricultural use by reducing the levels of salinity, exchangeable Na, and B in the soil, thereby increasing both crop yields and the number of crop species that can be grown in a specific area. Adverse levels of these substances can, however, be caused by other factors as well, including: under-irrigation (not providing enough water for leaching), inadequate drainage, and the use of moderately saline-sodic waters for irrigation. Use of such poor-quality waters is increasing due to growing municipal demands for the available supplies of good-quality water and the need to dispose of municipal waste waters and agricultural drainage waters. As a result, a solid understanding of soil reclamation will become an increasingly important component of water and soil management to assure the long-term sustainability of irrigated agriculture.

A key factor in salt-affected soil reclamation is water movement into and through soils. Infiltration rates (IR) and hydraulic conductivities (HC) decrease with decreasing soil salinity and with increasing exchangeable Na. Infiltration rates are more strongly affected by low soil salinity and exchangeable Na levels than are hydraulic conductivities because of the mechanical impact and stirring action of the applied water. During reclamation farmers must maintain adequate IR and HC through various combinations of crop, soil amendment, and tillage practices. Furthermore, drainage (either natural or artificial) must be adequate so that salts, exchangeable Na, and B are removed from the root zone.

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Our emphasis in this chapter is on basic soil and plant sciences as applied to reclamation and on documenting practices used by farmers in developed and developing countries. Physical, chemical, and mineralogical properties of soil are discussed in Section II. Specific reclamation examples and methods related to soil, water, and cropping practices are discussed in Sections III and IV. The final section describes farming practices used in California, Israel, and India for reclamation. We have drawn heavily on recent reviews: Gupta and Abrol (1990), Keren (1990), Rhoades and Loveday (1990), and Sumner (1993).

II. SALINITY AND SODICITY EFFECTS ON SOIL PHYSICAL PROPERTIES

Reclamation research and practice has a long history throughout many areas of the world. Most of this historical information remains valuable today. One of the problems with making use of this wealth of information, however, is a history of confusing and sometimes contradictory terminology that has been used to describe the different types of salt-affected soils. Therefore, we begin with a brief overview of some basic terms of soil classification, both in order to provide a historical perspective on reclamation research and to describe how such terms will be used in this chapter.

Historically, the physical behavior of salt-affected soils has been described in terms of the combined effects of soil salinity, as measured by the electrical conductivity of a saturation extract (ECe), and exchangeable sodium percentage (ESP) on flocculation and soil dispersion. The U.S. Salinity Laboratory Staff (1954) described the physical properties of a saline soil (ECe > 4 dS/m; ESP < 15) as follows: "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." A saline-alkali soil (ECe > 4 dS/m; ESP > 15) was described as similar to a saline soil "as long as excess salts were present." However, "upon leaching, the soil may become strongly alkaline (pH readings above 8.5), the particles disperse, and the soil becomes unfavorable for entry and movement of water and for tillage." It is clear, particularly from the last quote, that the authors linked the ESP guideline to an ECe that stabilized the soil, and that the value of 15 for ESP would have been lower had the authors chosen a lower value for ECe than 4 dS/m.

By 1979, the term "alkali" was listed as obsolete by the Soil Science Society of America (though it is still used by farm advisors and others) and the word "sodic" was listed in its place (Anonymous, 1979), with the definition, "a soil having an ESP > 15." Outside the USA, the word "alkali" is generally used in a narrower context referring only to soils: (i) with both high sodicity and high pH (ESP > 15, pH > 8.3), and (ii) containing soluble bicarbonate and carbonate (Na/[Cl + SO4] > 1) (Gupta & Abrol, 1990). In this context the term "alkali" has merit because swelling and dispersion increase as both ESP and pH increase (Gupta et al., 1984; Suarez et al., 1984), and soil solutions where sodium and bicarbonate plus carbonate are the predominant ions tend to have both low salinities and high pH values. The pH of sodic soils, on the other hand, can be either greater or less than 7 (Kelley, 1951, p. 78–81; Rengasamy & Olsson, 1991) and such soils can be either saline or nonsaline. Use of the term "alkali" thus allows practical distinctions between saline, sodic and alkali soils in terms of soil management (Bhumbla & Abrol, 1979; Gupta & Abrol, 1990). In this chapter, "saline" and "sodic" are used as defined by the Soil Science Society of America (Anonymous, 1979), while "alkali" is used as defined in this paragraph.

Despite the usefulness of such simple numerical criteria, it is important to recognize their limitations. For example, research conducted since 1954 has documented many instances in which the tendency for swelling, aggregate failure, and dispersion increases as salinity decreases even if the ESP is less than three—that is, nonsaline soil can behave like a sodic soil (Rengasamy et al., 1984; Shainberg & Letey, 1984; Sumner, 1993). These tendencies increase as ESP increases, requiring increasingly higher salinities to stabilize the soil. The boundary between stable and unstable conditions varies from one soil to the next. In addition, the stability boundary for water entry into a soil (infiltration) is different than that for water movement through the soil (unsaturated and saturated hydraulic conductivity): soil surfaces are more sensitive to low salinity, Mg (Keren, 1991), and exchangeable Na than is the soil underneath. In short, the numerical criteria used to differentiate between saline, saline-alkali, and nonsaline-alkali soils (U.S. Salinity Lab. Staff, 1954) give only one point on what is actually a salinity-sodicity continuum. It is important to understand this continuum and its impact on management guidelines for reclamation and subsequent water and soil management.

A. Clay Swelling and Dispersion

Clay swelling and dispersion are the two mechanisms that account for changes in hydraulic properties and soil structure (Shainberg & Letey, 1984; Quirk, 1986). Swelling that occurs within a fixed soil volume reduces pore radii, thereby reducing both saturated HC (Quirk & Schofield, 1955; McNeal et al., 1966; Rengasamy et al., 1984) and unsaturated HC (Russo & Bresler, 1977; Jayawardane, 1992; Xiao et al., 1992). Swelling results in aggregate breakdown, or slaking (Cass & Sumner, 1982; Abu-Sharar et al., 1987), and clay particle movement, which in turn lead to blockage of conducting pores (Quirk & Schofield, 1955; Rowell et al., 1967; Rhoades & Ingvalson, 1969; Felhendler et al., 1974).

Soil clay content is important in influencing the stability of soil structure and hydraulic properties because of the large surface area of clay particles, their thin platy shape, and their negative lattice charge, which is balanced by exchangeable cations. The type of clay also is important. A dominant clay mineral in semiarid and arid regions is montmorillonite. Kaolinite is common in more humid regions, while illite is common to both regions. The latter minerals, in their pure state, swell and disperse much less than montmorillonite. However, kaolinitic and illitic soils that contain low percentages of montmorillonite tend to be dispersive (Schofield & Samson, 1954; Frenkel et al., 1978).

The negative lattice charge of the clay and the exchangeable cations which reside in the liquid immediately adjacent to the particles form a diffuse double layer. Exchangeable ions are subject to two opposing tendencies: (i) electrostatic attraction to the negatively charged clay surfaces, and (ii) diffusion from a high concentration at the surface of the particle to a low concentration in the bulk solution. The result is an exponentially decreasing exchangeable ion concentration from the clay surface to the bulk solution. Since divalent ions are attracted to the surface with a force considerably greater than monovalent ions, the thickness of the diffuse double layer is more compressed for divalent ions. Increasing the salt concentration also compresses the double layer, because it reduces the tendency of exchangeable ions to diffuse away from the surface.

When two clay platelets approach each other, their diffuse double layers overlap and work must be done to overcome the electrical repulsion forces between the two positively charged exchangeable ion atmospheres. This repulsive force also is called the "swelling pressure." The greater the compression of the exchangeable ions toward the clay surface, the smaller the overlap of ionic atmospheres and the smaller the swelling pressure. Consequently, both clay swelling and the swelling pressure between particles decrease with increasing salt concentration of the bulk solution and increasing valence of the exchangeable cations. Sodium montmorillonite swells freely in dilute salt solutions, and single clay platelets tend to persist in these solutions. However, when divalent cations are adsorbed on montmorillonite surfaces, individual platelets aggregate into packets, or quasicrystals (Quirk & Aylmore, 1971), four to nine layers thick (Shainberg & Letey, 1984; Sposito, 1984). When this happens, only the external surfaces of calcium and magnesium quasicrystals participate in swelling, and swelling is much less than for sodium montmorillonite.

The distribution of Na/Ca in mixed cation systems deserves special consideration. Swelling of calcium montmorillonite is small and increases only slightly with small increases in ESP. Only when ESP exceeds 20 does swelling increase greatly (Quirk, 1968; Shainberg et al., 1971). Similarly, the size of calcium montmorillonite quasicrystals changes little at ESP < 20, though higher levels cause quasicrystal breakdown (Shainberg & Otoh, 1968). On the other hand, the initial increment of exchangeable Na causes a disproportionate increase in both the electrophoretic mobility of calcium quasicrystals (Bar-On et al., 1970) and the salt concentration required to flocculate calcium/sodium montmorillonite suspensions (Oster et al., 1980). These observations are explained by the "demixing" of the exchangeable ions: the initial increments of Na adsorb on the external surfaces of calcium quasicrystals, whereas adsorbed Ca remains in the interlayers between individual clay platelets. Consequently, the size of the quasicrystals does not increase with the initial increments of Na adsorption, though their electrophoretic mobility increases greatly. The sodium ions on the external surfaces of the quasicrystals impart to them a mobility similar to that of sodium montmorillonite and cause a disproportionate increase in the salt concentration required for flocculation.

B. Dispersion of Illites and Kaolinites

The effect of exchangeable Na on the flocculation values of calcium-illite suspensions follows a simple linear relationship (Oster et al., 1980) which suggests that "demixing" in sodium/calcium illite doesn't occur. However, under similar ESP and salt concentrations, illite suspensions were more dispersed than montmorillonite suspensions. Illite particles, which consist of platelets stacked to a thickness of about 10 nm, have rough edges that mismatch upon close approach, resulting in smaller attraction forces. Thus, higher salt concentrations are required for flocculation of illite than for montmorillonite. Similarly, Goldberg and Forster (1990) reported results for soil clays and pure clay systems that suggest illites in soils may play a primary role in determining dispersibility of the clay fraction.

Schofield and Samson (1954) found that a pure sodium kaolinite flocculated at pH < 7 under conditions where dispersed illite and montmorillonite remained dispersed. At this pH, planar faces of kaolinite crystals were negatively charged and the edge surfaces were positively charged, with resulting attraction between positive and negative charged surfaces causing flocculation. Deflocculation of the salt-free suspension occurred with the addition of NaOH. At pH > 8, the edges became negatively charged, resulting in deflocculation and dispersion. Suarez et al. (1984) reported similar results for two out of three soils studied. At pH 9, the saturated HC values of a montmorillonitic soil and a kaolinitic soil were lower than at pH 6, whereas pH did not affect HC for a vermiculitic soil. In addition to increased clay dispersion with increasing pH, Gupta et al. (1984) reported that additions of farmyard manure to the same soil also increased clay dispersion, a likely result of the adsorption of organic polyanions on positively charged surfaces of clay minerals (Durgin & Chaney, 1984; Shanmuganathan & Oades, 1983).

Positive edge charges of soil clays also can be decreased by adsorption of sodium montmorillonite (Schofield & Samson, 1954). Frenkel et al., (1978) found that the HC of a kaolinitic soil was not affected by an ESP of 20, but when the soil was mixed with 2% montmorillonite, the soil mixture was very susceptible to dispersion. Stern et al. (1991) and Ben-Hur et al. (1992) arrived at similar conclusions for South African soils which were predominantly kaolinitic and illitic but contained small amounts of montmorillonite.

Aluminum and iron hydroxides and oxides, common constituents of most soils, occur as coatings on clay minerals. It is generally accepted that the various forms of Al and Fe present in soils promote clay flocculation and reduce clay swelling and dispersion under sodic conditions (Deshpande et al., 1968; McNeal et al., 1968; Goldberg & Glaubig., 1987).

C. Effects of Sodicity and Salinity on Soil Hydraulic Properties

Soil HC depends on both the ESP of the soil, or the sodium adsorption ratio, SAR[1], of the soil solution, and the salinity of the soil solution (Fireman & Bodman, 1939; Quirk & Schofield, 1955; McNeal & Coleman, 1966). Here it is

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[1] SAR has units of $(\mathrm{mmol/L})^{1/2}$ because

$$SAR = \frac{C_{Na}}{\sqrt{C_{Ca} + C_{mg}}}$$

where ion concentrations C are in mmol/L. Following conventional usage, SAR values in the text will not include these units.

important to note that the SAR of the soil solution approximately equals the ESP of the soil in the range from 0 to 40. The higher the SAR and the lower the salinity, the larger the reduction in HC. Typical effects of salinity and SAR on the HC of soils from the western USA are shown in Fig. 19–1 (adapted from McNeal & Coleman, 1966). Each soil responds differently to the same combination of salinity and SAR because of differences in clay content, clay mineralogy, iron and aluminum oxide content, and organic matter content.

Quirk and Schofield (1955) introduced the concept of "threshold concentration," or salt concentration at which a 10 to 15% decrease in HC may occur for a given SAR. A plot of threshold concentration against SAR for a British soil (threshold concentration, Quirk & Schofield, 1955, Fig. 19–1) resulted in an approximately linear line for 0 < SAR < 60. Salt concentrations, or soil salinities, to the right of the line for the British soil were greater than the threshold for a given SAR, and the HC was stable. Hydraulic conductivities were not stable at concentrations to the left of the line, because salinity levels were inadequate to prevent swelling and/or dispersion.

With the exceptions of the Vale (mesic Aridic Argiustolls) and Aiken (mesic Xeric Haplohumults) soils (McNeal & Coleman, 1966; Aiken not shown on graph), 25% reductions in HC were associated with higher salinities than the "threshold concentration" associated with 10 to 15% reductions for the British soil (Quirk & Schofield, 1955). In other words, the Oasis (mesic Xeric Torrifluvents), Grangeville (thermic Fluvaquentic Haploxerolls), Pachappa (thermic Mollic Haploxeralfs), and Waukena (thermic Typic Natrixeralfs) soils were

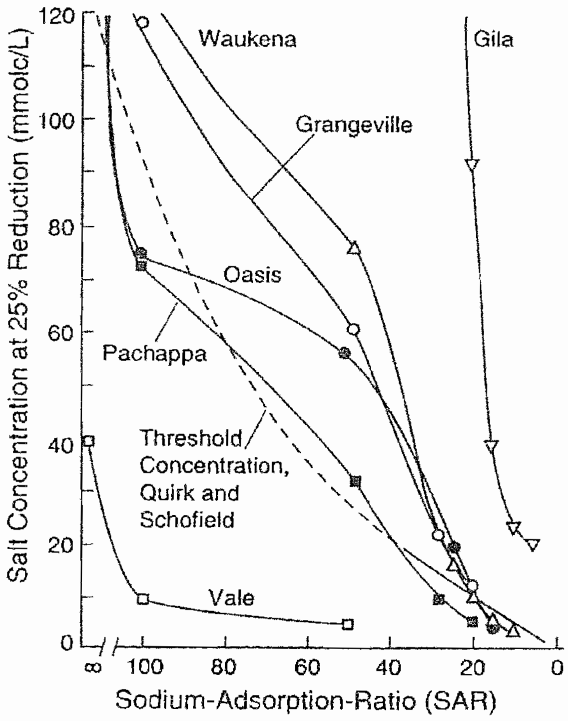

Fig. 19–1. Combinations of salt concentration and sodium adsorption ratio (SAR) required to produce a 25% reduction in hydraulic conductivity (HC) for selected soils from the western USA (McNeal & Coleman, 1966).

somewhat more sensitive to salinity than the British soil and Gila was much more sensitive. Research continues on the development of methods to predict the influence of the EC and ESP on hydraulic conductivities. Using data obtained by Russo and Bresler (1977) for a loam soil, Jawawardane (1992) obtained predicted saturated and unsaturated HC that were in reasonable agreement with the measured values using an "equivalent salt solution" concept which is based on solutions with combinations of SAR and EC that produce the same extent of clay swelling for a given soil. Further work is needed to develop methods to predict the effect of soil physical properties, such as clay content and mineralogy, on the two empirical coefficients required by the "equivalent salt solution" concept. These coefficients currently are determined for a soil from one set of measured saturated HC values as a function of EC for a given SAR.

In summary, swelling and dispersion increase with increasing SAR and decreasing salinity, thereby influencing the physical properties of each soil in a unique manner (Pratt & Suarez, 1990). Significant reductions (10–25%) in saturated HC for soils with SAR (or ESP) values of 15 can be expected if soil salinity is less than 5 to 50 mmolc/L (0.5–5 dS/m). Based on research conducted since 1966, similar reductions can be expected for soils with SAR (or ESP) values as low as three if soil salinity is less than 0.2 to 1 dS/m.

D. Effect of Sodicity and Salinity on Infiltration Rate

When water is applied to the soil surface at a rate that exceeds IR, whether by rainfall or irrigation, some penetrates the surface and flows into the soil, while the remainder fails to penetrate and instead either accumulates at the surface or runs off. Generally, the rate of water entry into the soil, or IR, is high during the initial stages of infiltration but decreases exponentially with time to approach a constant rate. Two main factors cause this drop in IR: (i) a decrease in the matric potential gradient which occurs as infiltration proceeds, and (ii) the formation of a seal or crust at the soil surface. In cultivated soils from semiarid regions, the organic matter content is low, soil structure is unstable, and sealing is a major determinant affecting the steady-state IR (Duley, 1939; McIntyre, 1958; Morin & Benyamini, 1977). Seal formation at the soil surface is in turn due to two processes: (i) physical disintegration of soil aggregates and soil compaction caused by the impact of water, especially water drops; (ii) chemical dispersion and movement of clay particles and the resultant plugging of conducting pores. Both of these processes act simultaneously, with the first enhancing the second (Agassi, 1981).

Infiltration rates are especially affected by the sodicity (SAR) and EC of irrigation water, because of the mechanical and stirring action of falling water drops, overland water flow, and the relative freedom of particle movement at the soil surface (Rengasamy et al., 1984). In studies in which waters of different qualities were applied to cropped columns of a loam (Udic Haploborall) soil, Oster and Schroer (1979) obtained a considerably better correlation of final IR of a cropped loam soil to the SAR and EC of the applied water than to the SAR and EC of the soil solution averaged over the total length of the soil column, 530 mm, or for the surface soil (0–76 mm).

In arid regions where irrigation is essential for maintaining agricultural production, the occasional rain may lower soil solution EC below the flocculation value, resulting in soil dispersion and severe reductions in IR. Similar conditions occur where nonsaline irrigation waters (~0.10 dS/m) are used for irrigation, such as along the east side of the central valley of California. The effect of soil ESP on the IR of a sandy loam subjected to rainfall is presented in Figs. 19–2a and 19–2b (Kazman et al., 1983). Increasing the ESP of the sandy loam soil (Fig. 19–2a)

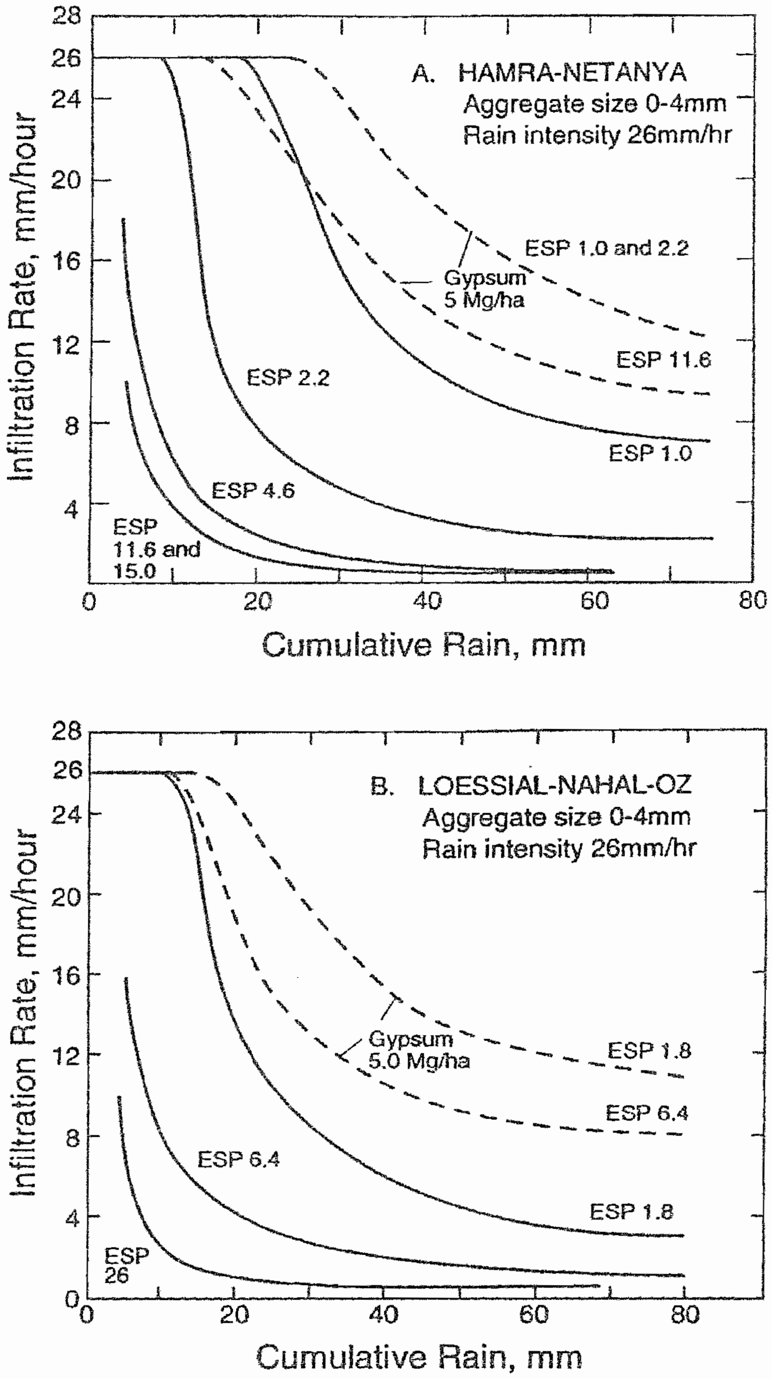

Fig. 19–2. Effects of ESP and phosphogypsum on the infiltration rate of a Hamra-Netanya sandy loam (*A*), and a loessial-Nahal-Oz soil (*B*) (Kazman et al., 1983).

from 1.0 to 2.2 dropped the final IR from 7.5 to 2.3 mm/h; increasing the ESP to 4.6 dropped the final IR to 0.6 mm/h. Similar results were obtained with the loessial silt loam (Fig. 19–2b). For both soils, spreading phosphogypsum at the soil surface was effective in reducing seal formation and the associated drop in IR (Fig. 19–2). Phosphogypsum dissolves and increases the EC and Ca content of the soil solution, reducing clay dispersion and seal formation.

Magnesium is not as effective as Ca in improving IR. At a given ESP, replacing exchangeable Ca with Mg enhanced the rate of IR decline and lowered the final IR for the soils used to obtain the data in Figs. 19–2a and 19–2b (Keren, 1991). This specific effect of Mg was attributed to the difference in size between hydrated magnesium and calcium ions, with resulting differences in strength of attraction to cation exchange sites. Hydrated magnesium, which is larger than hydrated calcium, decreases the linkages between external surfaces within a soil aggregate, in turn decreasing the amount of raindrop energy needed to break down soil aggregates.

E. Effects of Soil Mineral Equilibria on Soil Electrical Conductivity, Sodium Adsorption Ratio and pH

What constraints do soil minerals impose on the chemical composition of the water and exchange phases of a soil ongoing reclamation? Upon leaching with rainfall or with nonsaline irrigation water, the EC of the soil solution will not decrease below a level which depends, to a considerable degree, on soil mineral dissolution. Dissolution, in turn, depends on the soluble minerals present in the soil and on associated chemical equilibria that involve the compositions of the solid, exchanger, liquid, and gaseous phases of the soil (Oster & Halvorson, 1978; Abrol et al., 1979). Arid land soils release 3 to 5 mmolc/L of Ca and Mg to the soil solution as a result of the dissolution of plagioclase feldspars, amphiboles, pyroxenes, and other minerals (Rhoades et al., 1968). Dissolution of calcite and gypsum can maintain Ca, bicarbonate and sulfate concentrations at even higher levels, depending on the exchangeable ion composition and the partial pressure of carbon dioxide, PCO_2 (Oster & Rhoades, 1975; Oster, 1982). For soils that contain calcite, gypsum, or both, salinity increases linearly with SAR of the soil solution for a fixed Mg/Ca and PCO_2 (Fig. 19–3) after leaching has removed the soluble salts.

The line labeled Mg = 0; PCO_2 = 0.032 *k*Pa in Fig. 19–3 represents the calculated linkage between EC and SAR of the soil solution for a calcareous Na/Ca soil at partial pressure of 0.032 kPa (0.00032atm) that does not contain any chloride or sulfate salts. For a similar soil, the next lower solid line represents the EC/SAR linkage where concentrations of Ca and Mg are equal and the PCO_2 is 10 *k*Pa (0.1 atm). These two lines bracket likely minimum soil salinities that can occur during reclamation of calcareous sodic soils, particularly with rainfall. During reclamation with irrigation water, chloride and sulfate salts in the irrigation water would increase the soil salinity of a calcareous sodic soil.

Minimum salinities for soil solutions saturated with gypsum (Fig. 19–3) are greater than for solutions saturated with calcite, because gypsum is considerably more soluble. Magnesium also increases the minimum salinity, but PCO_2 has no effect. Because of common-ion effects between Ca, bicarbonate, and sulfate, the

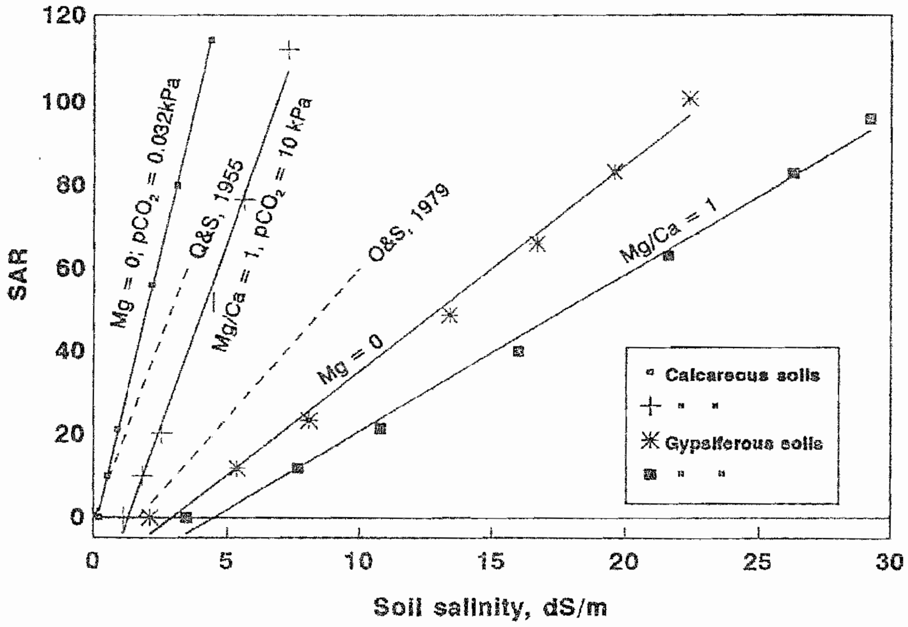

Fig. 19–3. Impact of SAR, pCO_2, and Mg: Ca ratio on minimum soil solution salinities for calcareous and gypsiferous soils. The broken line labeled Q&S represents the combinations of EC and SAR that resulted in a 10 to 15% reduction in K of a British soil (Quirk & Schofield, 1955). The dotted line labeled O&S represents the combinations of EC and SAR that resulted in a 25% reduction in steady-state IR of a North Dakota loam soil (Oster & Schroer, 1979).

minimum salinities for gypsiferous soils are independent of PCO_2 and are nearly the same as those for soils that contain both gypsum and calcite (Oster, 1982). During reclamation with irrigation water, only the chloride salts in the water would further increase the minimum soil salinity of a gypsiferous sodic soil.

Like minimum salinities, pH also depends on equilibrium constraints imposed by the presence of calcite (Gupta et al., 1981) or gypsum. The corresponding pH for the line labeled as Mg = 0; PCO_2 = 0.032 kPa in Fig. 19–3 ranges from 8.4 for an SAR of zero to 9.6 for an SAR of 100. For the next solid line to the right, the pH ranges from 6.9 for an SAR of zero to 7.6 for an SAR of 100. The difference in pH between the two lines results from the higher partial pressures of CO_2 for the lower line (10 kPa vs. 0.032 kPa), as well as the higher concentration of Mg. The PCO_2 in the root zone is a dynamic parameter which depends on microbial and root respiration and on soil water content. Values may range from 0.32 kPa near the soil surface to about 10 kPa in the lower portions of a rapidly respiring root system (Buyanovsky & Wagner, 1983). Increases in PCO_2 benefit the HC of sodic soils for two reasons: (i) the minimum salinity is higher, and (ii) the pH is lower.

F. The Physics and Inorganic Chemistry of Hydraulic Conductivities and Infiltration Rates: A Synthesis

The lines in Fig. 19–3 labeled "Q&S, 1955" and "O&S, 1979" provide quick comparisons of threshold salinities for HC and IR with minimum salinities for calcareous and gypsiferous soils. The EC/SAR combinations to the right of the "Q&S, 1955" line are likely to result in less than 10 to 30% reductions in HC. Similarly, EC/SAR combinations to the right of the "O&S, 1979" line are likely to result in less than 20 to 30% reductions in steady-state IR. These comparisons can be summarized as follows:

1. Minimum salinities for calcareous soils during reclamation with rain or low-salinity irrigation waters may not be adequate to meet threshold salinity requirements for HC, unless PCO_2 is enhanced by cropping (Robbins, 1986) or the soil contains significant levels of Mg (Alperovitch et al., 1981). Further, minimum salinities for calcareous soils will usually not meet threshold IR for soils where the SAR of the near-surface soil solution exceeds five unless the irrigation water contains sufficient chloride and sulfate salts to meet the threshold requirements.
2. For soils that contain gypsum, minimum salinities can be expected to meet the threshold salinity requirements for HC. This may not be true for IR, however. Salinity at the surface will depend on soil gypsum content, quantity of gypsum applied to the surface, dissolution kinetics of gypsum and the soils infiltration rate (Oster, 1982). It also will depend on the presence of any chloride salts in the irrigation water.

III. RECLAMATION OF SALINE SOILS

A. General Considerations

In ideal soils under piston-flow conditions, the EC of soil water and applied water would be equal after the passage of one pore volume of rainfall or irrigation water. However, soils are not ideal for two reasons: (i) Water flows faster through soil cracks and large pores between soil aggregates than through smaller pores within aggregates. This difference in localized water flow velocities is commonly referred to as bypass flow, or preferential flow. (ii) Salt diffusion coefficients and chemical reactions are not sufficiently rapid to allow salt concentrations to be the same among all pores of differing sizes, particularly during periods of rapid water movement.

Salt transport models have provided considerable insight into these processes (Dutt et al., 1972; Tanji et al., 1972; Robbins et al., 1980; Bresler et al., 1982). However, suitable mathematical methods are not available to describe the multiple concurrent processes of water flow, including spatially variable IR and HC, and all the chemical reactions—exchange, salt dissolution and precipitation, CO_2 liquid/gas equilibria—involved in salt transport on a field scale. Consequently, reclamation guidelines are largely based on experimental relations obtained from field and lysimeter reclamation experiments.

Method of water application and soil type are the primary variables affecting the amount of water required to reclaim saline soils. Hoffman (1986) summarized leaching results of several field reclamation studies. For saline soils, 60% or more of the salts initially present will be leached (or removed) by a depth of water equal to the depth of soil (Fig. 19–4) under continuously ponded conditions. Hoffman proposed the following relationship between the fraction of initial

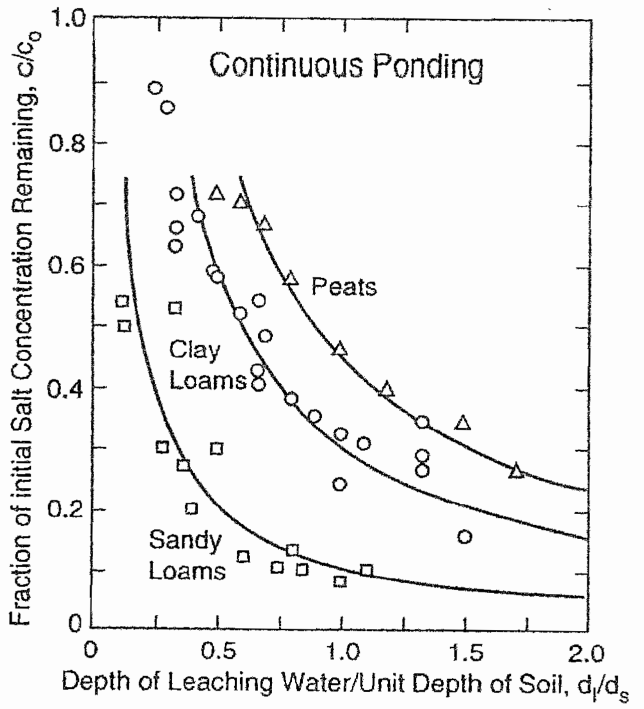

Fig. 19–4. Depth of leaching water per unit depth of soil required to reclaim a saline soil by continuous ponding (Hoffman, 1986).

salt concentration remaining in the profile, c/c_o , and the depth of water infiltrated, D_w, through a given depth of soil, D_s

$$(C/C_o)\ (D_w/D_s) = K, \qquad [1]$$

where HC differs with soil type. For reclamation with continuous ponding, the HC values for peat, clay loam, and sandy loam soils are 0.45, 0.3, and 0.1, respectively. The data in Fig. 19–4 for sandy loams are from two experiments in India (Leffelaar & Sharma, 1977; Khosla et al., 1979) and one in Iraq (Hulsbos & Boumans, 1960). The data for clay loams are from three tests in Utah on a clay loam (Xeric Torrifluvent), a silty clay loam (mesic Xeric Torrifluvents), and a clay (Reeve et al., 1948) and two tests in California, on a clay loam (hyperthermic Typic Torrifluvents) (Reeve et al., 1955) and a silty clay (hyperthermic Typic Torrifluvents) (Oster et al., 1972). Data on peat soils are from Turkey (Beyce, 1972, p. 63–84), with a field experiment conducted in California (Prichard et al., 1985) providing additional data that support the peat soil relationship. As defined, D_w in Eq. [1] does not include evaporation losses. Consequently, where evaporation is greater than 0.1 times D_w, D_w should be corrected for evaporation (Minhas & Khosla, 1986).

Equation [1] is valid only when (D_w/D_s) exceeds K. Differences in K reflect differences in saturated volumetric water content and leaching efficiency among soils. Sandy loam soils with low saturated water contents have higher leaching efficiencies than finer-textured soils. Soil pores in sandy soils are more uniform in diameter than in clay loam or clay soils. These finer-textured soils can have large cracks with large pores between aggregates and along crack surfaces when dry, and fine pores within aggregates when wet. Such bypass channels reduce leaching efficiency.

B. Intermittent Application: Ponding and Sprinkler Irrigation

The water requirement for leaching can be reduced by intermittent applications of ponded water, particularly for fine-textured soils. This reduces the constant, *K*, in Eq. [1] to 0.1 for silty clay, loam, and sandy loam soils (Fig. 19–5). Agreement among experiments is excellent considering that soil texture ranged from silty clay (hyperthermic Typic Torrifluvents) (Oster et al., 1972) to loam and sand (Talsma, 1967) and that the depth of water applied each cycle varied from 50 to 150 mm, with corresponding ponding intervals varying from weekly to monthly. For the fine-textured soil, the water requirement for intermittent ponding is only about one-third of that required by continuous ponding to remove 70% of the soluble salts. However, intermittent ponding techniques may be slower than continuous ponding. Although 50% more water was required for reclamation with continuous ponding, the time required for leaching a clay loam soil (thermic Typic Haplocambids) was much longer for intermittent ponding (Miller et al., 1965). For a silty clay soil, however, the same reclamation was achieved in 90 d using continuous ponding, intermittent ponding, and sprinkler irrigation (Oster et al., 1972).

With sprinkler irrigation, reclamation can occur under continuously unsaturated conditions if water application rates are controlled so ponding does not

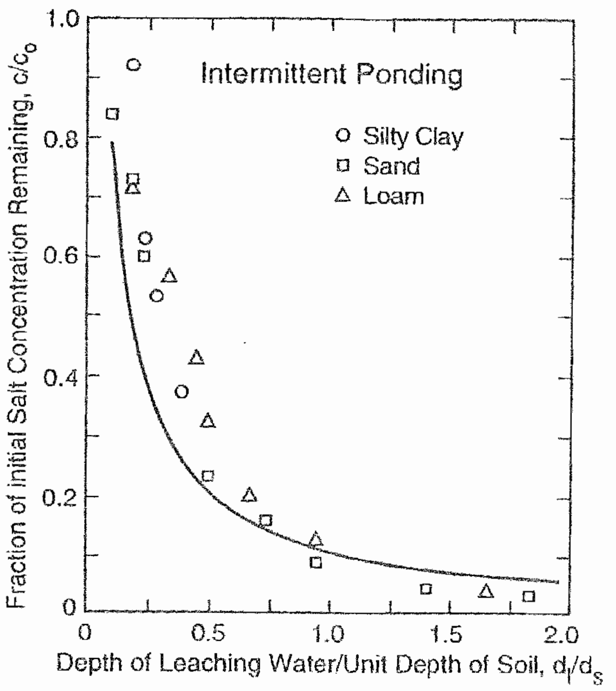

Fig. 19–5. Depth of leaching water per unit depth of soil required to reclaim a saline soil by ponding water intermittently (Hoffman, 1986).

occur. This circumvents inefficiencies caused by bypass flow in large cracks. Leaching occurs only within the depth of soil wet by sprinkler irrigation. If sprinkler irrigation occurs more frequently than intermittent ponding, the time-averaged water content within the depth wet by sprinkler irrigation can be higher than under intermittent ponding. The counteracting effects of reduced bypass flow and increased water content are consistent with the observed order of leaching efficiency (intermittent ponding > sprinkler > continuous ponding) in a field experiment conducted on a silty clay (Oster et al., 1972).

C. Reclamation of Saline Soils under Cropped Conditions

Leaching also is necessary for reclamation under cropped conditions, because salt removal by agronomic crops is insignificant. The average amount of salt contained in five mature forage crops [alfalfa (*Medicago sativa* L., barley (*Hordeum vulgare* L.), corn (*Zea mays* L.) silage, sudangrass (*Sorghum drummondii*) and sweetclover (*Melilotus* spp.) is about 0.4 Mg/ha (Longenecker & Lyerly, 1974). Another example involves the salt content of *Diphlachne fusca* (L.) Beauv., or *Leptochloa fusca* (L.) kunth (Booth, 1983), called Karnal grass in India and Kallar grass in Pakistan, a crop grown during reclamation of saline-sodic soils. The salt content ranges from 4 to 8% when grown in soils with ECe values of about 20 dS/m (Malik et al., 1986). Assuming a yield of 10 Mg/ha, the salt content of forage removed from such a field would range from 0.4 to 0.8 Mg/ha. This amount is small when compared to the salt content of saline soils, or of the irrigation water used to grow the crop. The salt content of a root zone 1 m deep that has an electrical conductivity of 20 dS/m is about 40 Mg/ha, the salt content of 10 ML (1 ha-m or 10 ML) of irrigation water with a salinity of 1 dS/m is about 6 Mg. Plants that are very efficient in removing salt from saline soils, such as sea-blithe (*Suaeda fruiticosa*), remove less than 3 Mg/ha per harvest (Chaudri et al., 1964).

Although cropping during reclamation is a common practice, only a few crops can tolerate high salinity levels, particularly during early stages of crop growth. Consequently, leaching before planting any crop is advisable when soil salinity is high (ECe > 10–15 dS/m) in the upper 1 m of soil. High salinity levels in the seed bed delay seed germination and reduce plant vigor during seedling establishment. It also is difficult to maintain adequate soil water contents and prevent crusting if rainfall or additional irrigation is required during a prolonged period of seed germination and plant establishment. Thus, to assure good crop establishment, salinity levels in the seed zone need to be considerably below threshold salinity levels for the crop (Maas & Grattan, 1999, see Chapter 3) which are generally based on crop response to salinity after plant growth is well established. In the San Joaquin Valley of California, for example, salinity levels (ECe) greater than 2 dS/m in the seed zone of cotton (*Gossypium hirsutum* L.) (threshold salinity of 7.7 dS/m) add 5 to 7 d to the normal 10 d required for germination and seedling establishment (Fulton, private communication). Crops such as rice (*Oryza sativa* L.) and Karnal grass that can be germinated or transplanted under ponded conditions circumvent problems with soil salinity during seedling establishment. For example, prewetted rice seed, which in California is "flown on" (distributed onto ponded fields from airplanes), is primarily exposed to the low salinities of the ponded water, as is the extensive surface root system that develops after seedling establishment. Similarly, transplanted rice plants can be established in nurseries with low soil salinities and transplanted into ponded saline soils at a more tolerant growth stage.

Provided that appropriate salinity conditions for the seed zone can be met, the choice of salt-tolerant crops depends in part on yield reductions that are acceptable and on the existing average root zone salinity (Table 19–1). Soil salinities for 0, 20, and 50% yield reductions were calculated from data reported by

Table 19–1. Yield potentials as a function of average rootzone salinity (adapted from Maas & Grattan, 1999).

Crop	Average root zone salinities (dS/m) at specific yield potentials		
		%	
	50	80	100
A. Grain/forage/fiber			
Triticale (grain) (*X. Tritocosecale*)	26	14	6
"Probred" wheat (grain) (*T. aestivum*)	25	15	9
Wheat (forage) (*Triticum aestivum*)	24	12	4
Durum wheat (forage) (*T. turgidum*)	22	10	2
Karnal grass[†] (*Diplachne fusca*)	20	8	3
Durum wheat (grain) (*T. turgidum*)	19	11	6
Barley (grain) (*Hordeum vulgare*)	18	12	8
Cotton (*Gossypium hirsutum*)	17	12	8
Rye (grain) (*Secale cercale*)	16	13	11
Sugarbeet (*Beta vulgaris*)	16	10	7
Bermuda grass (*Cyonodon Dactylon*)	15	10	7
Sudan grass (*Sorghum sudanese*)	14	8	3
Wheat (grain) (*T. aestivum*)	13	9	6
Barley (forage) (*H. vulgare*)	13	9	6
Berseem clover (*T. alexandrinum*)	10	5	2
Narrow leaf birdsfoot trefoil (*I. corniculatus tenuifolium*)	10	8	7
Sorghum (*Sorghum bicolor*)	10	8	7
Alfalfa (*Medicago sativa*)	9	5	2
Rice (paddy) (*Oryza sativa*)	7	5	3
Corn (forage) (*Zea mays*)	9	5	2
Corn (grain) (*Z. mays*)	6	3	2
B. Vegetables			
Asparagus (*Asparagus officinalis*)	29	14	4
Zucchini squash (*C. Pepo Melopepo*)	10	7	5
Celery (*Apium graveolens*)	10	5	2
Red beet (*Beta vulgaris*)	10	6	4
Spinach (*Spinacia oleracea*)	9	5	2
Eggplant (*Solanum Melongena esculantum*)	8	4	1
Broccoli (*Brassica olera cea botrytis*)	8	5	3
Tomato (*Lycopersicon Lycopersicum*)	8	4	2

[†] Malik et al., 1986.

Maas and Grattan (1999). The crops included in Table 19–1 are a select list of moderately sensitive to tolerant food, fiber, forage, and vegetable crops that are commonly grown and for which accurate salt tolerance data are available. Vegetable crops are included because they grow primarily during the cooler parts of the year and thus have relatively low water needs. In addition, vegetable crops have shallow roots and are not generally affected by high salinity or B levels below the root zone.

It should be noted that many moderately sensitive to tolerant crops included in the tables reported by Maas and Grattan (Chapter 1) are not listed in Table 19–1. Thus, the genetic diversity of crop salt tolerances provides many options for growing a range of crops during soil reclamation.

D. Reclamation of Soils with High Levels of Boron

Boron is toxic to most crops at soil solution concentrations exceeding a few milligrams per liter (Chapter 3). Boron is more difficult to leach than salts because it is adsorbed on clay minerals, hydroxy oxides of Al, Fe, and Mg, and organic matter (Keren & Bingham, 1985). Further, in soils with high levels of native B, reduced B concentrations immediately following leaching may be only temporary. Concentrations can increase with time, or regenerate, due to slow release of previously adsorbed B (Rhoades et al., 1970; Bingham et al., 1972), especially during the early stages of soil reclamation. Figure 19–6 shows reclamation results obtained under field conditions for two California soils high in native B (Indio clay loam-hyperthermic Typic Torrifluvents and thermic Typic Haplocambids) (Reeve et al., 1955; Bingham et al., 1972). Using Eq. [1] to fit the

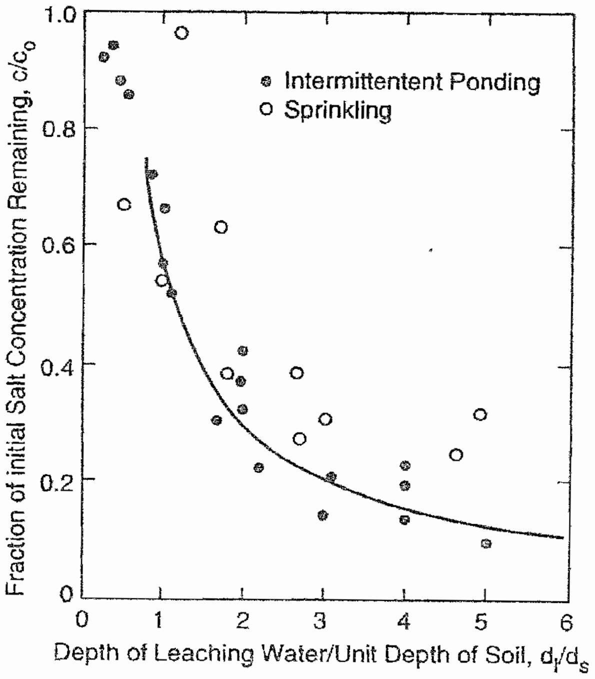

Fig. 19–6. Depth of leaching water per unit depth of soil required to reclaim a soil high in B (Hoffman, 1986).

data results in a *K* value of 0.6 (Hoffman, 1986). The water required to remove a given fraction of B by intermittent ponding or sprinkling is thus about two times greater than that required to remove soluble salts by the least effective method, continuous ponding. In addition, further periodic leaching may be required if B regeneration occurs.

Crops that are among the most tolerant of B include (from least to most tolerant) barley, sugar beet, tomato, sorghum, garlic, cotton, celery, onion, and asparagus. Yield potentials of 80% occur at soil-solution concentrations of 8 mg/L for barley, 12 mg/L for garlic, 16 mg/L for celery, and 20 mg/L for onion (Maas & Grattan, 1995).

IV. RECLAMATION OF SODIC SOILS

This section describes specific cases in which exchangeable Na affects the reclamation process. The focus is on maintaining adequate soil salinity to counteract the adverse effects of exchangeable Na on soil hydraulic properties. Salinity is the key to rapid reclamation as demonstrated by Reeve and Doering (1966) in the reclamation of clay loam soil using the high-salt-water dilution method. The subsections are ordered in terms of decreasing soil salinity: reclamation using the high-salt-water dilution method, reclamation of gypsiferous soils, reclamation of sodic soils using gypsum amendments, and reclamation of calcareous sodic soils using cropping techniques.

A. Reclamation with Saline Water (High-Salt-Water Dilution)

Hypersaline irrigation water can cause large increases in soil HC without the need of a soil for tillage, or cropping, or both. Equilibrations with successive dilutions of a hypersaline saline water will reduce both ESP and ECe. For a sandy loam soil with an ESP of 37, irrigation with Salton Sea water (560 mmolc/L) resulted in an HC of 5 mm/h (Reeve & Bower, 1960) as compared to 0.2 mm/h for irrigation with Colorado River water (11 mmol_c/L). In a field experiment conducted on a native, untilled clay loam (thermic Typic Haploxeralfs) ($70 < \text{ESP} < 80$, and $16 < \text{ECe} < 21$ in the upper 900 mm of soil), hydraulic conductivities of 0.05, 0.07, 4.17, and 10.95 mm/h were obtained for Colorado River water (11 mmol_c/L), Colorado River water saturated with gypsum (38 mmol_c/L), seawater (611 mmolc/L), and calcium chloride solution (655 mmol_c/L), respectively (Reeve & Doering, 1966). After continuous ponding for 238 d the ESP of the upper 150 mm of soil was reduced from 70 to 57 by Colorado River water and from 74 to 32 by gypsum-saturated Colorado River water, but in both cases the ESP at greater depths remained the same or even increased. In contrast, the ESP of the entire upper 900 mm of soil was reduced from 70 to 22 in 167 d by continuous ponding with successive dilutions of seawater ranging in concentrations from 600 to 75 mmol_c/L (final SAR = 11 and EC = 2 dS/m), and from 70 to 18 in 3 d with successive dilutions of calcium chloride solutions ranging in concentrations from 600 to 11 mmol_c/L (SAR = 0, final EC = 5 dS/m). Following reclamation with calcium chloride, the HC for Colorado River water was the same as for the last calcium chloride solution. In other words, after the ESP was reduced, the electrolyte concentration of Colorado River water was sufficient to maintain soil HC.

Muhammed et al. (1969) investigated the possibility of reducing the water requirement for reclamation of the same clay loam (mesic Xeric Torrifluvent and mesic Xeric Torrifluvents) by saturating the successive dilutions of seawater with gypsum and applying only enough water to achieve one-half of full equilibration for each successive dilution step. Application of their results (Oster, 1993) to the data obtained by Reeve and Doering (1966) results in a water requirement of 1500 mm water/900 mm of soil, or 1.7 mm water/mm soil. This scaled water requirement is similar to that for an 82% reduction in salinity under ponded conditions for clay loam soils (Eq. [1]).

Use of the high-salt-water dilution method should be considered wherever saline waters are available. However, the EC should exceed 20 dS/m, and the ratio of divalent cation concentration to total cation concentration should exceed 0.3 (with concentrations expressed in $\mathrm{mmol_c/L}$). If necessary, this ratio can be increased by the addition of gypsum, using, for example, the technique proposed by Keisling et al. (1978). Potential sources of highly saline waters include underlying groundwaters, nearby saline inland lakes, and ocean estuaries. The major problems with this technique are the facilities required to collect, convey, and treat the saline water, and the need to collect and dispose of highly saline drainage water in order to avoid contamination of surface and ground waters.

Reclamation of Gypsiferous Sodic Soils

Because of the high salinities of sodic soils that contain gypsum (Fig. 19–3), these soils are usually reclaimed successfully by leaching without additional amendments. For example, IR's after 48 h ranged from 7 to 9 mm/h during reclamation of two clay loam soils (mesic Xeric Torrifluvent and mesic Xeric Torrifluvents) ($30 < \mathrm{ESP} < 40$) under ponded conditions using an irrigation water with an EC of 2.5 dS/m and an SAR of 6 (Reeve et al., 1948). The gypsum content in the upper 600 mm of soil was sufficient to replace most of the exchangeable Na. In the same study, surface application of gypsum increased the infiltration rate from 8 to 14 mm/h for a clay soil which did not contain sufficient gypsum.

For a lysimeter experiment Jury et al. (1979) reported similar success with sandy loam (thermic Typic Torrifluvents) and clay loam sodic soils which contained gypsum, both from continuous applications of water using surface ponding and from daily applications at an unsaturated rate of about 0.4 mm/h, with irrigation water salinities of about 0, 0.5, and 1.3 dS/m. Infiltration rates were unaffected by irrigation water salinity even in the most extreme case, a clay loam soil reclaimed with distilled water: it sustained an infiltration rate of 4.5 mm/h for 3.6 pore volumes of drainage. The K value for Eq. [1] with this data is 0.29 (Oster, 1993), which agrees with the 0.30 constant obtained by Hoffman (1986) for saline soil reclamation during ponding for five soils. Three of the five reclamation studies in Hoffman's data base were those conducted on gypsiferous soda soils by Reeve et al. (1948), suggesting that gypsum in sodic soils does not affect the water requirement for reclamation. This K value for gypsiferous soils applies across a spectrum of soil textures ranging from sandy loam to clay. The data of Jury et al. (1979) also suggest that bypass water flow, hydrodynamic dispersion, and gypsum-dissolution kinetics do not affect the water requirement under conditions where water application rates range from 0.04 to 8 mm/h.

C. Reclamation of Sodic Soils with Underlying Gypsiferous Layers

In locations where sodium-affected surface soils are underlain by soil containing significant quantities of gypsum, deep plowing has been effective in breaking up and mixing the layers while supplying soluble Ca to aid reclamation. The depth of plowing required may vary from 0.5 to more than 1.0 m, depending on the concentration and depths of the sodium- and calcium-rich layers. A procedure is available to predict the optimum depth of plowing to maintain adequate permeability during the reclamation process (Rasmussen & McNeal, 1973).

D. Reclamation of Sodic Soils with Gypsum and Other Amendments

Gypsum, either incorporated into the soil or left on the surface, is the Ca source most commonly used to reclaim sodic soils and to improve water infiltration that has been decreased by low salinities. Sources include mineral deposits and phosphogypsum, a byproduct of the phosphate fertilizer industry. When gypsum is incorporated into the soil, the reduction in ESP upon irrigation and leaching is primarily limited to the soil depth interval where it is present (Fig. 19–7a). This is a consequence of the greater selectivity of exchange sites for Ca than for Na. The exchange phase of the soil, in the presence of gypsum, is an effective sink for Ca, which replaces exchangeable Na. The salinity of the soil solution (Fig. 19–7b) within and below the gypsum-amended layer decreases as the ESP within the amended layer decreases (Khosla et al., 1979; Oster & Frenkel, 1980; Frenkel et al., 1989). Only as reclamation approaches completion within the amended soil layer does the gypsum that dissolves begin to replace exchangeable Na at greater depths. During this second phase of reclamation, the required threshold salinity levels in lower soil layers may not be maintained, resulting in decreased HC. A

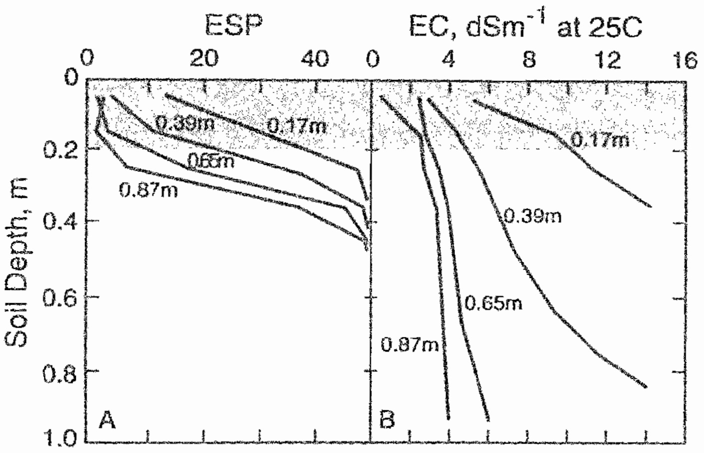

Fig. 19–7. Computer-modeling results (ESP and EC) for reclamation with gypsum of a soil with a cation exchange capacity of 200 mmolc/kg using an irrigation water with an EC of zero. The initial ESP of the soil was 50 at all depths; the numbers next to each line are the depths of applied water in meters (Oster & Frenkel, 1980).

decrease in HC during partial soil reclamation is consistent with HC data reported by Robbins (1986) obtained from 1-m long lysimeters during a reclamation study of a calcareous sodic silt loam soil: (i) greatest reclamation occurred within the upper 0.2 m of the uncropped gypsum-treated lysimeters, the layer in which adequate gypsum was incorporated to reclaim the upper 0.5 m of soil (Fig. 19–8a); and (ii) the water flow rate declined to near zero in the gypsum-treated lysimeters after reclamation in the upper 0.2 m was complete and one pore volume of drainage had been collected.

The gypsum required (GR) for reclamation, in Megagrams per hectare, can be calculated using Eq. [2]

$$GR = 0.0086\,(F)\,(D_s)\,(\rho_b)(CEC)\,(ESP_i - ESP_f) \qquad [2]$$

where F (unitless) represents the Ca-Na exchange efficiency factor, Ds is the soil depth (m), b is the soil bulk density (Mg/m^3), CEC is the cation exchange capacity ($mmol_c/kg$), and ESP_i and ESP_f represent the initial and final exchangeable Na percentages. The efficiency factor ranges from 1.1 for an ESP_f of 15 to 1.3 for an ESP_f of 5 (Oster & Frenkel, 1980). The SAR can be substituted for ESP in the range $0 < SAR < 50$.

A laboratory method also can be used to determine GR, but the values tend to be high. The Schoonover procedure (U. S. Salinity Lab. Staff, 1954, Procedure 22d) determines the amount of Ca required to replace all the exchangeable Na plus any that is precipitated by soluble bicarbonates and carbonates in the soil. Since these soluble ions are leached during sodic-soil reclamation, Abrol et al. (1975) proposed a modified procedure. It includes leaching 5 g of soil with 20 mL of 60% ethanol to remove soluble bicarbonate and carbonate, followed by equilibration with 100 mL of a calcium sulfate solution (30 $mmol_c/L$). The difference between the Ca concentration in the calcium sulfate solution and the Ca plus Mg concentration ($mmol_c/L$) in a clear filtrate of the soil suspension, times 20, equals $CEC\ ESP_i - ESP_f$ in Eq. [2], or $CEC(ESP_i)$ since ESP_f is zero after equilibration with the calcium sulfate solution.

Other amendments used for calcareous sodic soils include sulfuric acid and acid formers such as S, lime sulfur, pyrite, and iron and aluminum sulfates. These amendments react with calcite, thereby providing a soluble source of Ca within the soil. Equivalent quantities of chemically pure amendments relative to a ton of gypsum or sulfur are given in Table 19–2.

Table 19–2. Amounts of amendments equivalent to one ton of either gypsum or S.

	Formula	Gypsum	S
Gypsum	$CaSO_4 2H_2O$	1.00	5.38
Calcium chloride	$CaCl_2 2H_2O$	0.85	4.59
Sulfur	S_8	0.19	1.00
Iron sulfate	$FeSO_4 7H_2O$	1.61	8.69
	$Fe_2(SO_4)_3 9H_2O$	1.09	5.85
Aluminum sulfate	$Al_2(SO_4)_3 18H_2O$	1.29	6.94
Iron pyrite	FeS_2, 30%S	0.35	1.87

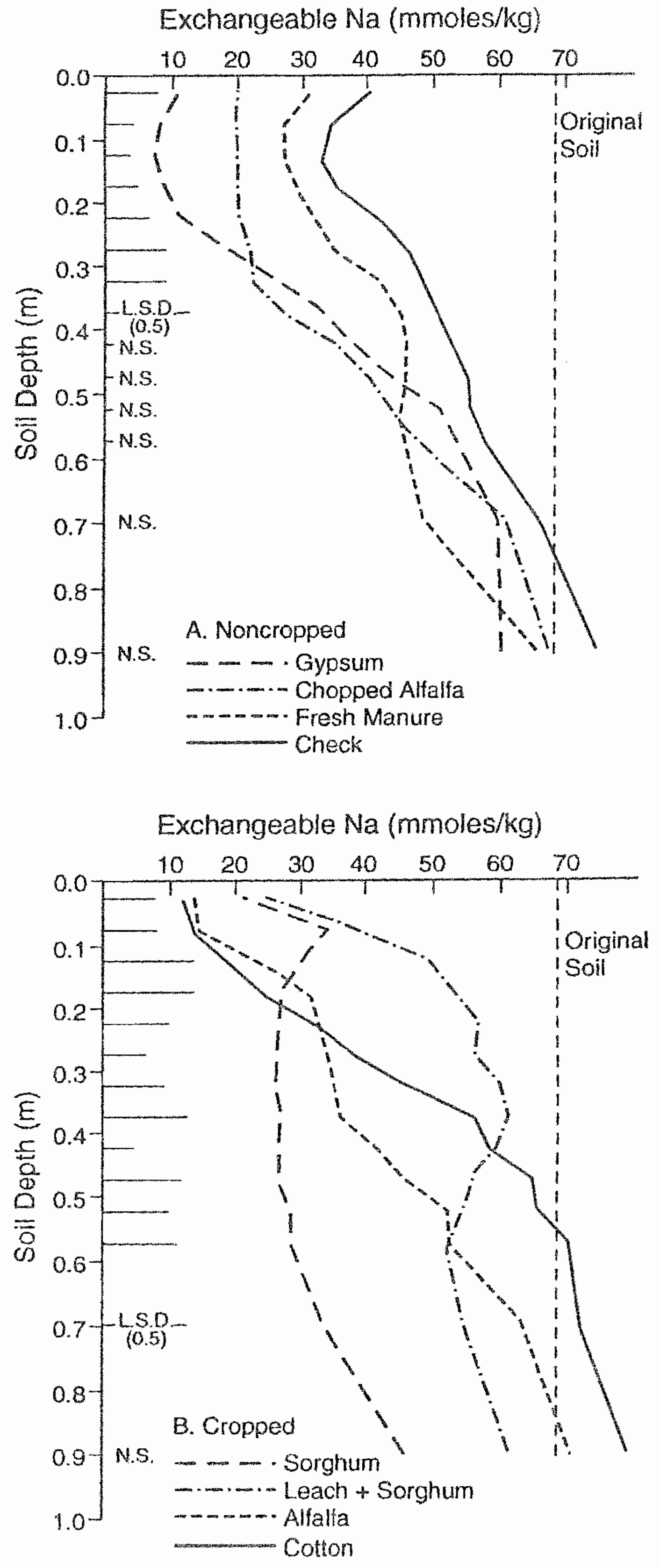

Fig. 19-8. Final distribution of exchangeable Na levels with soil depth resulting from reclamation treatments for noncropped (*A*) and cropped (*B*) treatments (Robbins, 1986).

The following chemical reactions illustrate how various amendments react with calcareous sodic soils. In these reactions *X* represents the soil exchange complex.

1. Inorganic Reactions
   Gypsum ($CaSO_4 \cdot 2H_2O$)
   $$2NaX + CaSO_4 \cdot 2H_2O \Leftrightarrow CaX_2 + Na_2SO_4 + 2\,H_2O$$
   Sulfuric acid (H_2SO_4)
   $$2NaX + H_2SO_4 + CaCO_3 \Leftrightarrow CaX_2 + Na_2SO_4 + CO_2 + H_2O$$
   Iron sulfate ($FeSO_4 \cdot 7H_2O$)
   $$4NaX + 2FeSO_4 + 2CaCO_3 + 1/2\ O_2 \Leftrightarrow 2CaX_2 + 2Na_2SO_4 + Fe_2O_3 + 2CO_2$$
2. Microbiologically mediated reactions
   Sulfur (S_8)
   $$4NaX + 2S + 2CaCO_3 + 30_2 \Leftrightarrow 2CaX_2 + 2Na_2SO_4 + 2CO_2$$
   Iron pyrite (FeS_2)
   $$8\ NaX + 2FeS_2 + 15/2O_2 + 4CaCO_3 \Leftrightarrow 4\ CaX_2 + 4Na_2SO_4 + Fe_2O_3 + 4CO_2$$

Cost, availability, and time required for reaction with soil determine which chemical amendment will be best for specific circumstances. Calcium chloride, likely the most costly amendment, is the quickest to dissolve and react with the soil. Iron, aluminum sulfates and gypsum also react quickly when mixed with the soil. The finer the particle size of the solid amendments and the greater the uniformity of soil incorporation, the faster and more efficient the reclamation reactions.

Degree of crystallinity is another factor: phosphogypsum is a more porous crystal than mined gypsum, and therefore dissolves faster. This factor also may operate in the case of sulfuric acid, which reacts quickly with calcite and has been observed to be more effective than equivalent amounts of gypsum (Overstreet et al., 1951; Miyamoto et al., 1975). After the initial acid dissolution and exchange reactions are complete, additional calcite dissolution by sulfuric acid can result in gypsum precipitation. This gypsum is relatively noncrystalline, and its uniformity of incorporation exceeds any that could be achieved by mechanical incorporation of finely ground mined gypsum.

Sulfur and iron pyrite must be oxidized by soil microorganisms and are therefore both classified as slow-acting amendments. Since microbial activity increases with decreasing pH, it is important not to dilute these amendments by incorporating them too deeply into the soil. In other words, shallow tillage may be preferable to deep tillage. Since these reactions increase with increasing soil temperature (Overstreet et al., 1955), application is best during the spring and summer months.

E. Reclamation of Nonsaline Sodic (Alkali) Soils by Growing Crops

Reclamation practices often involve growing crops together with the application and infiltration of excess water during the cropping season. Benefits from cropping include the following: (i) Increased PCO_2 due to plant root respiration and decomposition of organic matter (Kelly, 1951; Chhabra & Abrol, 1977; Robbins, 1986; Gupta et al., 1989), which in turn increases soil salinity and decreases pH in calcareous soils (see Section II.E). Robbins (1986) demonstrated that "satisfactory" HC could be maintained with cropping treatments, whereas this was not the case for gypsum-treated soils which were not cropped. (ii) In-situ production of polysaccharides, which, in conjunction with differential dewatering at the root/soil interface, promotes aggregate stability (Boyle et al., 1989). (iii) The physical effects of root action (Chhabra & Abrol, 1977), including removal of entrapped air from the larger conducting pores (McNeal et al., 1966), generation of alternate wetting and drying cycles, and creation of macropores and release of CO_2 upon decomposition. (iv) Financial or other benefits from crops grown during reclamation that can help support farming operations.

In a lysimeter study, Robbins (1986) measured the partial pressure of CO_2 in the root zone during reclamation of a nonsaline (ECe = 2.4), sodic (ESP = 33), calcareous silt loam (CEC = 210 $\mathrm{mmol_c/kg}$) under cropped conditions. He demonstrated conclusively the benefits of increased soil atmosphere CO_2 concentrations for HC, with concurrent reduction of exchangeable Na. In the case of lysimeters cropped with a hybrid sorghum (*Sorghum bicolor* L. Moench), the amount of Na removed equaled that of noncropped lysimeters amended with gypsum. Reclamation for the gypsum-amended lysimeters (Fig. 19–8a), however, occurred primarily in the zone where gypsum was incorporated, whereas it occurred throughout the root zone (Fig. 19–8b) for lysimeters cropped with sorghum and alfalfa during the entire reclamation process. Leaching the soil before cropping (Fig 19–8B; leach + sorghum) resulted in low HC and subsequent poor plant growth.

F. Crop Selection

Crops grown during sodic soil reclamation must tolerate both poor soil physical properties (Gupta & Abrol, 1990) and Na-induced Ca deficiency characterized by necrotic curled leaf tips and heavily serrated leaves (Carter et al., 1979; Maas & Grieve, 1987; Grieve & Maas, 1988). High Na concentrations reduce the amount of Ca that is available for plant uptake (Cramer & Lauchli, 1986). Calcium concentrations that are adequate under nonsodic conditions (1–2 $\mathrm{mmol_c/L}$) can thus become inadequate when the Na/Ca of the soil solution is high (Bernstein, 1975). Seedling growth stages of cereals are particularly susceptible to Ca deficiency, though considerable variability occurs among crops (Grieve & Maas, 1988): Variability also occurs among genotypes of sorghum (Grieve & Maas, 1988), rice (Grieve & Fujiyama, 1987), triticale (Norlyn & Epstein, 1984), and wheat (Kingsbury & Epstein, 1986). The data for rice are of interest because rice is often recommended for growing during reclamation of sodic soils in India (Gupta & Abrol, 1990). For the rice cultivars M9 and M-201, Grieve and Fujiyama (1987) reported severe Ca deficiencies at an osmotic potential of (0.4 MPa (about 10 dS/m) and at an Na/Ca molar ratio of 78 (SAR = 87), whereas Yeo and Flowers (1985) reported no Ca deficiencies at Na/Ca molar ratios as high as 500 (SAR = 160) for cultivar IR2153. Based on limited data for seedlings of different crops, the general order of increasing susceptibility to Ca deficiency is rice cultivar IR2153, cotton, barley, wheat, rye, sorghum, cowpea (*Vigna unguiculata* L. Walp.) (Grieve, private communication, 1993). The wide diversity among crops and crop genotypes increases the likelihood that field trials conducted under nonsaline sodic conditions will identify local crops that are adaptable to sodic soil conditions.

Extensive areas of the Indo-Gangetic plains of northern India have calcareous sodic soils. Field plot studies at the Central Soil Salinity Research Institute near Karnal conducted since 1970 provide the crop tolerance results shown in Table 19–3 (adapted from Gupta & Abrol, 1990). Differential, nonsaline sodic conditions were obtained by applying different amounts of gypsum to the soil and leaching by ponding for about 20 d (Abrol & Bhumbla, 1979). The ESP values ranged from about 10 to 70, with a corresponding range in SAR of about 7 to 160. Crops were grown under both rainfall and irrigated conditions, with recommended agronomic, fertilization, and plant protection practices used for all treatments. Rankings in Table 19–3 are based on 50% yield reductions, with rankings of rice, barley, and wheat similar to those reported by Grieve. However, because of crop genotype variations and varying experimental conditions, this similarity could be fortuitous.

Table 19–3. Relative tolerance of crops to sodicity.

ESP range	Crops[†]	Genus
10–15	Safflower	*Carthamus tinctorius*
	Mash[‡]	
	Pea	*Pisum sativum*
	Lentil	*Lens esculenta*
	Pigeon pea	*Cajanus Cajan*
	Curd bean[‡]	
16–20	Bengal gram[‡]	
	Soybean	*Glycine max*
20–25	Groundnut	*Arachis hypogaea*
	Cowpea	*Vigna unguiculata*
	Onion	*Allium Cepa*
	Pearl millet	*Pennisetum glaucum*
25–30	Linseed	*Linum usitatissimum*
	Garlic	*Allium sativum*
	Guar	*Cyamopsis tetragonoloba*
30–50	Indian mustard	*Brassica juncea*
	Wheat	*Triticum aestivum*
	Sunflower	*Helianthus annuus*
	Berseem	*Tritalium alexandrinum*
	Hybrid napier	*Pennisetum purpureum*
	Guinea grass	*Panicum maximum*
50–60	Barley	*Hordeum vulgare*
	Sesbania	*Sesbania exaltata*
	Saftal[‡]	
60–70	Rice	*Oryza sativa*
	Para grass	*Panicum purpurascens*
70+	Karnal grass	*Diplachne fusca*
	Rhodes grass	*Chloris Gayana*
	Bermuda grass	*Cynodon Dactylon*

[†] Yields are about 50% of the potential yields in the respective sodicity ranges (adapted from Gupta & Abrol, 1990).

[‡] Colloquial name used in India.

In addition to the sodicity-tolerant crops listed in Table 19–3, grasses also can be grown on sodic soils. *Diplachne fusca* (Karnal or Kallar grass), *Chloris gayana* (Rhodes grass), and *Brachiaria mutica* (Para grass) have been reported as highly tolerant to sodicity (Kumar & Abrol, 1986). In addition, Karnal and Para grasses grow well under ponded conditions.

V. FIELD RECLAMATION PRACTICES

A. California

Reclamation of Saline and Sodic Soils

One interesting example of reclamation that combines tillage, ponding, and cropping is represented by practices in the Imperial Valley [ET_0 (potential evapotranspiration), 1900 mm; rainfall, 0–50 mm; T_{max}, 45°C, T_{min}, –2°C] through the early 1960s. Reclamation practices for calcareous and gypsiferous, saline-sodic soils (clay loam–silty clay) with Colorado River water (EC_e = 1.2 dS/m, SAR = 1.5) included tillage, land leveling, leaching by continuous ponding, and cropping. Tillage of dry fallow soils included either ripping or slip plowing (to depths of 1 or 2 m, respectively), followed by disking and contour disking. Ripping loosens plow pans, clay layers, and hard pans, whereas slip plowing mixes layers of different textures. Unusually large amounts of water will infiltrate during the first irrigation following either ripping or slip plowing of dry soils. Water was ponded between large border dikes during the fall and early winter months until salinities at the soil surface were less than 12 dS/m (R. S. Ayers, personal communication, 1992). The field was then prepared for furrow irrigation after the upper 30 cm had dried sufficiently to allow tillage. Cotton, grown between April and November, was then planted often on the side of the furrow slightly above the water level maintained during the germination irrigation (p. 44f in Ayers & Westcot, 1985). This provided additional leaching of the seed zone and prevented problems with seedling emergence due to soil crusting. Cotton was grown in rotation with barley, which was grown between December and June, until soil salinities were sufficiently low (based on spatial uniformity of crop growth and yields) to include alfalfa in rotation.

In the Central Valley of California the climate is cooler than in the Imperial Valley [ET_0 1400 mm; T_{max}, 43°C, T_{min}, –7°C], and rainfall (150–460 mm) occurs primarily during the winter months. Virgin soils were calcareous, containing a wide range of salinity, sodicity, gypsum and boron, particularly along the west side of the valley. Some of the virgin soils were nonsaline-sodic (Overstreet et al., 1955; Kelly, 1951). Cropping during reclamation was a common practice in this area. Chemical amendments were used selectively, with reclamation possible without them on many soils (Overstreet et al., 1955). Amendments such as gypsum and sulfuric acid (on calcareous soils) increased the rate of reclamation, with Overstreet et al. (1951) and Overstreet et al. (1955) reporting field data that indicate sulfuric acid is superior to gypsum. However, recent laboratory studies indicate that gypsum, sulfates of aluminum and iron, and sulfuric acid are equally effective when applied to moderately sodic calcareous, silty clay soils (Miyamota & Enriquez, 1990).

Generally speaking, California farmers tend to practice reclamation over the long term. For example, annual or semiannual gypsum applications of 2 to 4 Mg/ha to an entire field are continued as long as crop growth is uneven and yields are low. Amendment applications to small areas within a field with continually poor plant growth are made by some farmers, though this is not a typical practice.

Barley, a winter crop, was usually the first crop grown on new ground during reclamation in the 1950s and 1960s, with border irrigation used to supplement annual rainfall. After one or more barley crops, cotton was often added to the rotation. Cotton fields were ripped before planting, amended with gypsum if necessary, listed to create furrows, and preirrigated. Large amounts of water (250–350 mm) infiltrated during preirrigation, resulting in considerable leaching and reclamation. The following quote summarizes recommendations provided by the University of California at the time: "Field crops, particularly barley, wheat, sorghum, cotton, and sugar beet, are real tools for use in reclamation, or as transition crops to "get acquainted" with soils and to get from "where we are" to "where we want to be" from the standpoint of soil salinity, Na, and B. By utilizing *more water* on these crops than is actually needed, salts, Na, and B can be leached beyond reach of roots, and the soils can be prepared for later plantings of more sensitive high-income crops" (Dean's Committee, Univ. California, 1968). Reclamation using such methods required considerable time, since excess water necessary to reclaim the upper 5 ft of soil ranged from five feet for salinity to 15 ft for B (Bingham et al., 1972). Additional water is still generally required to compensate for spatial variability of soils and associated infiltration rates (Jaynes & Hundsaker, 1989; Wichelns & Oster, 1990), but with continuing efforts success eventually occurred. In the San Joaquin Valley of California, vineyards planted in the 1970s now exist in fields where reclamation of saline-sodic soils began in the 1950s.

Reclamation by one or two large, annual irrigations which usually occur before planting or during the first crop irrigation is a form of intermittent reclamation that also has been successful when practiced over the long term. Farmers along the west side of the San Joaquin Valley of California use ripping tools to till soils to depths of 0.5 to 0.75 m. Following disking, land planing and listing to prepare deep (0.3–0.4 m) furrows, 0.25 to 0.35 m of water infiltrates during the subsequent irrigation. Gypsum may be applied at rates of 2 to 4 Mg/ha either before or after tillage, depending on farmer experience with gypsum on a particular field or on soil analysis that indicates it would be beneficial. For cotton, the heaviest irrigation occurs 30 to 90 d before planting; then, several days before planting, the tops of the beds are removed ("decapped") and the cotton is planted into the exposed wet soil. In saline fields, the depth of decapitation is increased to assure that seeds are planted at a depth where the soil is less saline and wetter than if the decapitation were shallower.

Use of Gypsum to Maintain Infiltration Rates

Addition of gypsum to the soil surface (1–2 Mg/ha) or to irrigation water (3–5 mmol_c/L) for the purpose of maintaining infiltration rates also is a common practice in California. Doneen (1948) reported that 270 000 Mg of gypsum were applied in the San Joaquin Valley to improve infiltration. The addition of gypsum to Friant-Kern irrigation water (EC < 0.2 dS/m) or to the nonsodic soils irrigated with it was a common practice in the 1950s on the east side of the valley between Fresno and Bakersfield (R. S. Ayers, personal communication, 1980), and such practices are still common today. In recent years, machines to inject gypsum slurries into the irrigation water also have become available, and their use is increasing.

Gypsum particle size is an important consideration for both surface applications to soil and injection through the irrigation water. For land application, a typical particle size of commercially available gypsum (92% pure) in California is 87% finer than 2.4 mm, 52% finer than 0.3 mm, and 25% finer than 0.07 mm. Finer material is needed for injection into irrigation water, with a typical particle-size distribution of 99 to 100% finer than 0.15 mm, 93 to 97% finer than 0.07 mm, and 3 to 78% finer than 0.04 mm.

B. Israel

Sustained Irrigation With Saline-Sodic Groundwater

In the western Negev region of Israel there is a saline aquifer with EC values ranging from 2.5 to 8.5 dS/m and SAR values of 15 to 26. The dominant soils are silty loams and the climate is Mediterranean, with winter rainfall ranging between 250 and 400 mm. Cotton is the dominant crop.

The effect of 16 yr of irrigation with water from a well at Kibbutz Nahal-Oz (EC of 4.6 dS/m and SAR of 26) provides a typical example of ongoing reclamation practices. Irrigation during the summer (450 mm) results in ESP values of 20 to 26 in the upper 600 mm of soil. There is no deterioration in soil hydraulic properties during the summer due to the high EC of the irrigation water. However, deterioration does occur during the rainy season due to the low salt concentrations of the rainwater. To offset this, phosphogypsum is spread annually on the soil surface, following tillage in the fall, at a rate of 5 Mg/ha. This prevents seal formation and maintains high infiltration rates which, in turn, provide sufficient infiltration of rainfall to leach salts from the root zone. Fall application of phosphogypsum and leaching during the rainy season, coupled with adequate irrigation with the saline-sodic water to meet crop needs during the summer months, has resulted in seed cotton yields averaging 5 Mg/ha between 1979 and 1988. These yields were similar to those obtained when only nonsaline-sodic water was used for irrigation.

C. India

Reclamation of Nonsaline-Sodic or Alkali Soils

In the Indo-Gangetic plains of India, most farmers begin reclamation in the monsoon season (July–September; 600–900 mm rainfall) by growing rice. Exchangeable Na levels of the soil can be as high as 100%. Excess exchangeable Na, high pH, lack of adequate Zn and Ca, and the resulting poor soil physical conditions and nutritional properties are the chief causes for poor productivity.

Recommended practices for this area (Mehta, 1985; Singh, 1985; Gupta & Abrol, 1990) include the following: (i) dividing fields into subplots of 0.4 ha each, bordered by 0.4-m high dikes (bunds); (ii) leveling, locating high and low spots in the subplots using a shallow irrigation, and releveling with a slope of 0.1% towards the drainage channel; (iii) avoiding tillage while the soils are wet because of the poor physical properties of sodic soils; (iv) applying finely powdered gypsum (100% finer than 2 mm, 75% finer than 1 mm, and 35% finer than 0.125 mm) at rates of about 10-15 Mg/ha, depending on soil sodicity and texture to reduce the ESP of the surface 150 mm of soil to 15–20; (v) incorporating the gypsum in the top 60 to 80 mm of soil by shallow tillage; (vi) leaching for 15 to 20 d prior to transplanting rice, with recommended varieties including P2-21, IR 8, PR 106 and Basmati 370; (vii) installing tubewells and utilizing the pumped water for irrigation, particularly where water tables are high; and (viii) planting and transplanting three-leaf rice seedlings (35–45 d old) grown on reclaimed soil (rice seedlings are sensitive to sodicity at the 1 to 2 leaf stage).

If properly fertilized with N and Zn (Chhabra & Abrol, 1977; Singh, 1985; Gupta & Abrol, 1990), yields of dwarf rice varieties during reclamation can approach levels achieved in fully reclaimed soils when ESP values for the surface 150 mm are 60 or less (soil solution SAR values < 100). The intention of the initial amendment application is to reduce exchangeable Na to less than 25 to 30% so that excellent yields of rice and moderate yields of wheat can be obtained even during the 1st yr. Farmers often do not apply gypsum, but instead resort to prolonged leaching and accompanying application of farmyard manures. When this is done, rice yields are reduced, and rice may have to be grown for 3 to 5 yr before wheat can be grown with even moderate yields. Reclamation is not considered to be complete until the upper 600 mm of soil are fully reclaimed, i.e., soil ESP or soil solution SAR levels less than five. At this juncture, wheat yields approach maximum potentials, though the yields of more sensitive crops such as pea may still be reduced because of moderate sodicity levels below soil depths of 600 mm.

Diphlachne fusca or *Leptochloa fusca* (Karnal or Kallar grass) grows well under ponded conditions in saline-sodic soils (Kumar, 1985; Malik et al., 1986). Stem cuttings or root stolons are transplanted into flooded fields. This is a perennial plant and can be planted at any time of the year, but the best planting time is March, since growth is maximum during the summer. If irrigation is continued during the winter, one cutting can be obtained during winter months (as compared to three cuttings between spring and fall). Experiments conducted in Pakistan (Malik et al., 1986) indicate that N and P fertilizers have little effect on growth. Growing this grass for 3 to 4 yr results in sufficient reclamation to grow rice and wheat, without any need for further reclamation practices; however, market demand for the grass is small, limiting the usefulness of this reclamation method.

VI. CONCLUDING COMMENTS

The major thrust of this chapter has been on the technical side of the reclamation of saline-sodic soilsóthe scientific basis for reclamation, the relative effectiveness of different reclamation practices, and examples of successful reclamation practices from different areas of the world. However, there are two additional major factors that lie outside of agronomy as traditionally practiced in the USA which cannot be ignored by agricultural scientists, farm advisors, consultants and farmers.

Optimum reclamation practices depend on the soil problems requiring correction, the crops grown in the region, and the equipment available for soil tillage. In developed countries, mechanical power is available for deep tillage and other land preparation techniques (spreading and incorporation of chemical amendments, land leveling, preparation of high earthen dikes, etc.) required to prepare large areas of land (60–500 ha) so that large amounts of irrigation water can be applied and allowed to infiltrate. Cropping in conjunction with repeated tillage and heavy irrigation of saline soils or soils high in boron is a common practice, as is cropping of sodic soils where tillage is combined with application of amendments. Farmers in developing countries, who have only limited access to mechanical power, must rely more on crops like rice which can be grown in small fields under ponded conditions. Cropping in conjunction with reclamation is a popular method in both types of countries because it provides concurrent income; i.e., it is a "pay-as-you-go" option.

Reclamation also has significant environmental consequences: making the soil better in one place degrades soil and water resources somewhere else. Reclamation requires irrigation, drainage, and a place for salt disposal. Whether artificial tile drainage is installed or not, salts will be displaced downward into soil strata and ground waters beneath the irrigated land. Extensive reclamation often results in shallow saline water tables which may require installation of tile drainage. The resulting saline drainage water generally increases the salinity of receiving surface waters. These negative environmental impacts of reclamation require purposeful and long-term planning and education. Is the eventual environmental degradation acceptable? Will the increased productivity compensate for the degradation? Reclamation and subsequent irrigation without short- and long-term resolutions of drainage water disposal issues becomes, in the long run, the bane of irrigated agriculture. Agriculturists working in such areas must know how to reclaim soils with minimum environmental impacts; how to provide the necessary information to local farmers and help them learn how to use it; how to tell others what the tradeoffs are between food production and environmental consequences; and how to tell future generations what the economic and environmental tradeoffs are and will continue to be.

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