Managing Saline and Sodic Soils for Producing Horticultural Crops

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Summary. About 33% of all irrigated lands worldwide are affected by varying degrees of salinity and sodicity. Soil with an electrical conductivity (EC) of the saturated extract $>4 \text{ dS} \cdot \text{m}^{-1}$ is considered saline, but some horticultural crops are negatively affected if salt concentrations in the rooting zone exceed $2 \text{ dS} \cdot \text{m}^{-1}$. Salinity effects on plant growth are generally osmotic in nature, but specific toxicities and nutritional balances are known to occur. In addition to the direct toxic effects of Na salts, Na can negatively impact soil structure. Soil with exchangeable sodium percentages (ESPs) or saturated extract sodium absorption ratios (SARs) >15 are considered sodic. Sodic soils tend to deflocculate, become impermeable to water and air, and puddle. Many horticultural crops are sensitive to the deterioration of soil physical properties associated with Na in soil and irrigation water. This review summarizes important considerations in managing saline and sodic soils for producing horticultural crops. Economically viable management practices may simply involve a minor, inexpensive modification of cultural practices under conditions of low to moderate salinity or a more costly reclamation under conditions of high Na.

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Problems associated with salt and Na-affected soils have existed for thousands of years in locations ranging from Asia, the Middle East, Africa, South America, and North America. For example, one of the causes for the decline and disappearance of the native American Hohokam civilization in central Arizona is thought to be soil salinization of the Gila River Valley, which they irrigated (Bohrer, 1970). About 33% of all irrigated land worldwide is made up of saline soils (Yenson and Bedell, 1993). About 6 million ha of irrigated land is lost each year due to drainage and salinization problems (Bohn et al., 1985).

In addition, about 405 million ha of land is associated with saline aquifers. Problems of soil salinity and sodicity occur primarily in arid areas where evapotranspiration exceeds rainfall. However, under certain conditions, soil salinity problems exist in humid regions as well.

In the United States, 5 million ha in the 17 western states is classified as saline (Bohn et al., 1985). Many of these soils are used for producing horticultural crops. Several horticultural crops are sensitive to saline conditions and are strongly affected by the deterioration of soil physical conditions associated with Na. The objective of this paper is to review and summarize various considerations in managing saline and sodic soils used for producing horticultural crops.

Soil considerations

Chemical. The salt and Na status of the soil should be chemically characterized. The salinity status of a soil usually is determined by measuring the electrical conductivity (EC_e) of the water extract from the saturated soil paste. Soils are classified as being saline if EC_e exceeds $4 \text{ dS} \cdot \text{m}^{-1}$ (Table 1). However, many salt-sensitive horticultural crops, such as lettuce (*Lactuca sativa* L.), are harmed by $\text{EC}_e > 2 \text{ dS} \cdot \text{m}^{-1}$.

Sodicity refers to an excess of exchangeable Na in the soil. In addition to direct toxic effects from Na salts, Na negatively influences soil structure, thus rendering soils unsuitable for crop production. Sodic soils often are characterized by dispersed soil particles, low water permeability due to pore clogging and colloid swelling, poor aeration, high soil pH (>9), and dispersed organic matter (black alkali).

Soils with exchangeable Na percentages (ESPs) >15 are considered sodic. However, ESP values of 5 to 10 may reduce infiltration in some soils. Because determining ESP is tedious, the sodium absorption ratio (SAR_e) in water extracts from saturated soil pastes is often used.

$$\text{SAR}_e = (\text{Na}) / ((\text{Ca} + \text{Mg})/2)^{0.5} \quad [1]$$

where concentrations are expressed in meq/liter.

Although SAR_e has a chemical basis in the

Table 1. *Classification of salt- and sodium-affected soils.*

Criterion	Normal	Saline	Sodic	Saline-Sodic
EC _e (dS·m ⁻¹)	<4	>4	<4	>4
SAR _e	<15	<15	>15	>15

Table 2. *A comparison of salt levels and moisture contents for three soils.*

Salt level or moisture content	Sand	Loam	Muck
Soil situation			
EC _e (dS·m ⁻¹)	2.0	2.0	2.0
Dry soil weight (kg/15 cm-ha)	2,400,000	2,128,000	616,000
At saturation			
Water content (%)	24	40	150
Water (kg·ha ⁻¹)	576,000	851,200	924,000
Salt concentration (ppm)	1,280	1,280	1,280
Total salts (kg·ha ⁻¹)	737	1,090	1,183
At field capacity			
Water content (%)	6	20	140
Water (kg·ha ⁻¹)	144,000	425,600	862,400
Salt concentration (ppm)	5,118	2,560	1,370

theory of cation exchange (Sposito and Mattigod, 1977), we typically measure what has been called the practical SAR_e ratio, which is only empirically related to SAR_e and ESP. Statistical relationships derived from several soils indicate that practical SAR_e values are about 12% < SAR_e values and reasonably close to ESP values (Sposito and Mattigod, 1977). Hence, soils with practical SAR_e values >15 are generally considered sodic (Table 1).

Soil-water relationships. Interpretations of soil salinity status and its potential impact on plant growth can be somewhat confounded by soil-water relationships, which are largely influenced by soil texture and soil organic matter content. For example, consider a sand, a loam, and a muck soil all having an EC_e of 2 dS·m⁻¹ and containing 24%, 40%, and 150% moisture at saturation, respectively (Table 2). However, at field capacity (about 0.1 bar tension), moisture contents are 6% for sand, 20% for loam, and 140% for muck. Assuming no leaching, precipitation or plant uptake of salts, at field capacity the salt concentration in sand would be almost twice that of loam and almost four times that of muck. These complications are especially important for salt-sensitive crops such as lettuce, for which EC_e values >2 dS·m⁻¹ adversely affect plant growth in loam, whereas EC_e values >1.5 dS·m⁻¹ might negatively affect yield in sand.

Hammond (1966) suggested multiplying EC_e values by one half the ratio, saturation percentage moisture: field capacity moisture, to correct roughly for differences in water relationships among soils. When this type of soil moisture information is not available, a rule of thumb is to multiply values for sandy soils by 2 and values for muck soils by 0.5 before interpretation (Hammond, 1966). More re-

cently, as part of a research program directed toward developing technologies for measuring in situ bulk soil salinity (EC_a), more accurate models have been developed that interrelate EC_a and EC_e based on selected soil properties (Rhoades 1981; Rhoades et al., 1989a, 1989b, 1990).

Spatial variability. The salt and Na status of a field typically is determined from a composite soil sample. However, such a protocol ignores variation in salinity across a given field. Managing 10- to 20-ha units based on a composite soil sample might affect salt-sensitive crops adversely. Note the variation in EC_e from across a field in southwestern Arizona before being planted to lettuce (Fig. 1). Lettuce yield and quality would be compromised severely in one corner of this field should the entire field be managed based on the EC_e of about 2.1 of a composite soil sample.

Detailed mapping of soil salinity from EC_e measurement is generally impractical. However, field determination of soil-paste electrical conductivities (EC_p) (Rhoades et al. 1989a) and field measurements of bulk soil salinity (EC_a) using four electrode sensors, electromagnetic measurements, or time domain reflectometric sensors show promise as a practical means of assessing field variability (Lesch et al. 1992; Rhoades and Oster, 1986).

Because irrigation efficiencies in the southwestern United States are generally low (large leaching fractions and sometimes tail water) for many horticultural crops, field variability in salinity is

not a major problem at present. However, as irrigation efficiencies are enhanced, site-specific technologies for salt and Na management might prove economical.

Crop considerations

Osmotic effects. The general effects of bulk soil salinity on plants are osmotic. High salt concentrations in the plant rooting zone hinder the plant's ability to take up water from the soil solution. Plants often counter this osmotic gradient by osmotic adjustment, i.e., increasing their internal solute concentration, by producing organic acids or accumulating salts, usually K. However, this process requires energy that would otherwise be used for plant growth and development.

Tolerances to soil salinity have been established for most important crop species (Bernstein, 1964; 1974). Most economically important horticultural crops have been classified as moderately sensitive and sensitive to salinity. Specific tolerances, with respect to EC_e values for 0%, 10%, 25%, and 50% yield reductions, are shown for several economically important horticultural crops in Table 3. A more complete list can be found in Maas and Hoffman (1977) and Maas (1984). Recent publications establishing tolerances for additional horticultural crops (Francois, 1995) attest to the fact that this is an ongoing area of research.

Specific toxicities. In addition to general salinity effects, many horticultural crops are affected negatively by high concentrations of specific ions such as Cl, B, and Na (Fig. 2). Crop tolerances to Cl and B have been established for many economically important horticultural crops (Bernstein, 1965; Eaton, 1944; Maas, 1984; Pearson, 1960). For example, understanding the Cl tolerance for various citrus rootstocks is of utmost importance in selecting the appropriate rootstock

Fig. 1. Variability in soil EC_e values in a field in southwestern Arizona (Yuma Valley) before lettuce seeding. (Unpublished data provided by Agro Phosphate Inc.)

Table 3. *Yield potential of selected vegetable and fruit crops² as influenced by soil salinity (EC_e).*

Crop	Yield potential (%)			
	100	90	75	50
	EC _e dS·m ⁻¹			
Vegetable				
Broccoli (<i>Brassica oleracea</i> L. Italica)	2.8	4.9	5.5	8.2
Tomato (<i>Lycopersicon esculentum</i> Mill.)	2.5	3.5	5.0	7.6
Cucumber (<i>Cucumis sativus</i> L.)	2.5	3.3	4.4	6.3
Celery [<i>Apium graveolens</i> L. var. dulce (Mill) Pers.]	1.8	3.4	5.8	9.9
Cabbage (<i>Brassica oleracea</i> L. Capitata group)	1.8	2.8	4.4	7.0
Pepper (<i>Capsicum annuum</i> L. var. annuum)	1.5	2.2	3.3	5.1
Lettuce (<i>Lactuca sativa</i> L.)	1.3	2.1	3.2	5.1
Radish (<i>Raphanus sativus</i> L.)	1.2	2.0	3.1	5.0
Onion (<i>Allium cepa</i> L. cepa group)	1.2	1.8	2.8	4.3
Carrot (<i>Daucus carota</i> L.)	1.0	1.7	2.8	4.6
Bean (<i>Phaseolus vulgaris</i> L.)	1.0	1.5	2.3	3.6
Fruit				
Date palms (<i>Phoenix dactylifera</i> L.)	4.0	6.8	11.0	18.0
Grapefruit (<i>Citrus paradisi</i> Macf.)	1.8	2.4	3.4	4.9
Orange (<i>Citrus sinensis</i> L. Osb.)	1.7	2.3	3.3	4.8
Peach [<i>Prunus persica</i> (L.) Batsch]	1.7	2.2	2.9	4.1
Grape (<i>Vitis</i> sp.)	1.5	2.5	4.1	6.7
Plum (<i>Prunus domestica</i> L.)	1.5	2.1	2.9	4.3
Blackberry (<i>Rubus</i> sp.)	1.5	2.0	2.6	3.8
Strawberry (<i>Fragaria</i> sp.)	1.0	1.3	1.8	2.5

²Adapted from Maas and Hoffman (1977) and Maas (1984).

for specific conditions of soil and irrigation water (Table 4).

Many horticultural plant species are very sensitive to Na. Most deciduous fruit crops, citrus, and nut crops are affected by soil ESP levels as low as 5 (Pearson, 1960). Some vegetable crops are affected by ESP values as low as 10. These effects are observed even where soil physical conditions remain favorable, suggesting the effects are direct Na toxicity.

Nutritional imbalances. Salinity also affects plant growth by inducing nutritional imbalances. For example, high concentrations of monovalent salts in the rooting zone can reduce plant uptake of Ca (Fig. 3). Another example is bicarbonate-induced deficiencies of the micronutrients Fe, Zn, and Mn.

Cropping systems. Information of salinity tolerance also should be used in the context of cropping strategies. For example, a common cropping sequence in the low desert region of the southwestern United States is cotton and lettuce. While cotton is generally tolerant of saline conditions, lettuce is not. Hence, during cotton production, soils should be managed to preclude salt accumulation, which might adversely affect a subsequent crop of lettuce.

Water considerations

Water quality. The quality of water used for irrigation is a major consideration. The salinity status of water is assessed using EC measure-

ments. Based on statistical relationships developed from several waters, total dissolved solids (TDS mg·liter⁻¹) can be estimated by multiplying EC_w (dS·m⁻¹) values by 640.

Evapotranspiration concentrates salts added in irrigation water. Hence, irrigation water with modest amounts of salt can result in saline soil conditions. An assessment of irrigation water suitability must consider the salinity tolerance of the

crop, leaching volume achieved, and the predicted level of salinity in soil water from using this irrigation water (Rhoades, 1972).

In addition to total salts, the Na concentration of irrigation water is important. The Na hazard of irrigation water often is assessed using the SAR_w, the same ratio defined previously for soil extracts (SAR_e). If SAR_w values of irrigation water are >7 to 10, low water infiltration and conversion of the soil to sodic conditions may occur. However, the SAR_w alone neglects the potential sodium hazard associated with water high in bicarbonates. The carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) in irrigation water can precipitate Ca, thereby increasing the SAR of irrigation water.

Over the years, several methods have been proposed for predicting the potential Na hazard associated with carbonate and bicarbonate ions in irrigation water. The residual sodium carbonate (RSC) method was used commonly at one time (Eaton, 1950):

$$\text{RSC} = [\text{HCO}_3^- + \text{CO}_3^{2-}] - [\text{Ca}^{2+} + \text{Mg}^{2+}] \quad [2]$$

Waters with RSC >2.5 were considered unsuitable for irrigation purposes; waters with RSC of 1.25 to 2.5 were considered marginal; and waters <1.25 were considered safe (Wilcox et al., 1954). The RSC method assumes all HCO₃⁻ precipitates and generally overpredicts the Na⁺ hazard of water. This method has been abandoned largely in favor of adjusted SAR methods proposed by others (Bower et al., 1968; Rhoades, 1968; Suarez, 1981). Presently, the adjusted SAR method proposed by Suarez (1981) generally is favored, be-

Fig. 2. Chloride toxicity to furrow-irrigated grapes near Safford, Ariz. (Photograph courtesy of T. Doerge.)

Table 4. *Tolerance of citrus rootstocks to chloride in soil (Cl_e) and irrigation water.²*

Rootstock	Soil (Cl_e)	Irrigation water (Cl_w)
	<i>meq/liter</i>	
Sunki mandarin	25.0	16.6
Grapefruit		
Cleopatra mandarin		
Rangpur lime		
Sampson tangelo	15.0	10.0
Rough lemon		
Sour orange		
Ronkan mandarin		
Citrumelo	10.0	6.7
Trifoliate orange		
Cuban shaddock		
Calamondin		
Sweet orange		
Savage citrange		
Rusk citrange		
Troyer citrange		

²Adapted from Maas (1984).

cause it is simpler and more accurate than alternative procedures. This equation is discussed in more detail below with respect to leaching requirements.

Irrigation method. Irrigation method and volume of water applied have a pronounced influence on salt accumulation and distribution (Ayers and Westcot, 1989; Bernstein and Francois, 1973). Data collected from a citrus experiment conducted in southwestern Arizona show various salt distribution patterns as a result of different irrigation methods (Fig. 4). Flood irrigation and an appropriate leaching fraction generally move salts below the root zone. Similar results can be obtained with a properly managed sprinkler irrigation system. However, in hot, arid climates, evaporation loss during sprinkling might increase the salinity of water moving into the soil (Ayers and Westcot, 1989). Robinson's (1973) study suggests that the concentration of salts in sprinkler water for salt-sensitive crops is generally not a problem in the center of the field but may be a problem near the edge of the field, where evaporation losses are higher. Another major concern with sprinkler irrigation is the potential for leaf burn. Harding et al. (1958) reported that water normally suitable for surface irrigation may be harmful to citrus. They found that leaf burn and defoliation of the lower part of citrus trees can result from sprinkling water having EC_w values of 0.8 to 1.5 dS·m⁻¹. Tolerances of crops to foliar injury using sprinkler irrigation can be found in Maas (1984) and Ayers and Westcot (1989).

With furrow and pressurized irrigation, soluble salts in the soil move with the wetting front, concentrating at its termination or at its convergence with another wetting front. In drip-irrigated plots, water moves away from the emitter and salts concentrate where water evaporates. In furrow-irrigated crops, water movement is from the furrow

into the bed via capillary flow. When adjacent furrows are irrigated, salts concentrate in the center of the intervening bed (Fig. 5). Manipulating bed shape and planting arrangement are strategies often used to avoid salt damage in furrow-irrigated row crops. This is discussed in more detail below. Because drip irrigation maintains more constant favorable conditions of soil moisture, plants tolerate higher levels of salinity than with furrow irrigation (Bernstein and Francois, 1973).

Management strategies

Leaching. Leaching excess salts and maintaining favorable salt balance remains the best strategy to prevent detrimental salt accumulation in the soil profile. Leaching also can be used to reclaim nonsodic saline soils. Most leaching strategies are based on a steady-state assumption of mass balance and are calculated by

$$LF = D_{dw}/D_{iw} = EC_{iw}/EC_{dw} \quad [3]$$

where LF (leaching fraction) is the fraction of water that leaves the root zone as drainage water, D_{dw} and D_{iw} are the volumes of drainage and irrigation water, respectively, and EC_{iw} and EC_{dw} are the EC of irrigation water and drainage water, respectively. Typically EC_{dw} is selected from crop tolerance data (such as that presented in Table 4) to calculate the desired leaching fraction. Because salt concentrations of saturation extracts (EC_e values) are typically more dilute than the salt concentration of the actual drainage water under field con-

ditions, using EC_e values in the denominator of Eq. [3] (EC_{dw}) traditionally has exaggerated the calculated leaching fraction. As noted above, information on soil texture and soil moisture can be used to estimate bulk salinity in the rooting zone (EC_a values).

This above relationship also ignores ion uptake by plants and precipitation and dissolution reactions of carbonates in the rooting zone. Errors associated with the latter could have disastrous effects when water high in sodium or bicarbonate are used for irrigation. Several approaches have been used to estimate leaching fractions in which calcium carbonate tends to precipitate or dissolve in soils. Bower et al. (1968) proposed using a modified saturation index based on Langelier's index. However, this equation overpredicted the sodium hazard associated with drainage waters (Oster and Rhoades, 1975). Rhoades (1968) modified Langelier's index to include empirically derived parameters aimed at predicting mineral weathering. It worked well for many western soils. However, the value of the weathering coefficient varies somewhat with soil–water combination (O'Connor, 1971; Oster and Rhoades, 1975), thus limiting its

Fig. 3. *Celery blackheart*, a calcium-related physiological disorder. In this case blackheart was caused by a high concentration of monovalent salts in the rooting zone.

predictive potential. Suarez (1981) proposed the following:

$$\text{Adj SAR}_{\text{dw}} = (\text{Na}_w/\text{LF}) / \{(\text{Mg}_w/\text{LF} + X(\text{P}_{\text{CO}_2})^{1/3})^{1/2}\} \quad [4]$$

where Na_w and Mg_w are the concentrations of Na and Mg in irrigation water as mmol-liter^{-1} , P_{CO_2} is the partial pressure of CO_2 in the soil, and X is selected from a table (Suarez, 1981) based on the HCO_3^-/Ca ratio and the ionic strength of the irrigation water (which is estimated by EC_w). Because this relationship is not very sensitive to P_{CO_2} , rough estimates are usually satisfactory. Equation [4] attempts to address shortcomings in previous equations by calculating equilibrium pH rather than assuming one. This equation is simpler and generally more accurate than others used and has found widespread application in the western United States.

Drainage. A prerequisite to using leaching as a management tool is good internal and external drainage. Poor internal soil drainage caused by surface crusting, hardpans, and sodic conditions often is managed by tillage and soil amendments. Deep chiseling is performed at least once a year on

most cropland in the low desert of southwestern United States (Fig. 6). When sodic conditions exist, an aggressive soil amendment program usually is required.

External drainage on most farmland in the western United States is maintained through an intricate network of open drains and tile drains. In some situations, drainage wells are required.

Planting configuration, bed arrangement, and irrigation. Water movement in furrow irrigation is from the furrow into the bed. This can result in localized elevated salinity, which can harm seedling plants (Bernstein and Fireman, 1957), even under low to moderately saline conditions. Many crops, such as lettuce and broccoli, are seeded in two rows near the outer edge of the bed with a ridge or corrugation in the center. This arrangement places young seedlings out of the zone of highest salt accumulation. For crops such as cauliflower, which typically are seeded one row per bed, plants often are offset from the bed center, or only every other furrow is irrigated during stand establishment.

Other strategies also avoid gradients caused by furrow irrigation. Sprinkler irrigation during

stand establishment has become a widespread practice for vegetables produced in the low desert (Hartz, 1994). Sprinkling moves salts with water downward below the seed zone. Crops such as sweet corn can be planted in the water-furrow or planted in mulched moist beds to avoid salt accumulation associated with furrow irrigation. More details on options for bed and planting configurations with regard to salinity management can be found in Ayers and Westcot (1989).

Fertilizer management. Many fertilizers contain soluble salts in high concentrations. Therefore, nutrient source, rate, timing, and placement are important considerations in the production of horticultural crops. Salt indices for most commercial fertilizer products have been reported by Rader (1943). For example, KCl has a salt index 2.5 times that of K_2SO_4 . Generally, band application of fertilizers with high salt indices near seedlings should be avoided. An interesting example where source

Fig. 4. Salt distribution patterns below a 'Valencia' orange grove in southwestern Arizona (Wellton Mesa) as influenced by irrigation system. (Unpublished data provided by R. Roth.)

Fig. 5. Salt distribution in furrow-irrigated melons. Note melons are seeded on the south side of the bed away from the high concentrations of salts in the bed center. (Photograph courtesy of T. Doerge.)

may be important, even with broadcast application, is for lettuce production in southern Florida. During prolonged periods of no rainfall, K and other salts have the potential to accumulate near the soil surface as a result of upward movement with water from the subsurface irrigation systems. Field studies have shown that under these conditions lettuce yield reduction is more pronounced when KCl is used compared to K_2SO_4 (C.A. Sanchez, unpublished data).

The salt content of amendments such as gypsum and manures also should be considered. For many soils in the western United States, gypsum application is a useful management practice for precluding sodium accumulation on the soil's exchange complex, maintaining soil structure, and improving water infiltration. However, in a recent field study conducted near Yuma, Ariz., gypsum reduced growth and marketable yield of lettuce when applied immediately before seeding (C.A. Sanchez and J.C. Silvertooth, unpublished data). Hence, for salt-sensitive crops such as lettuce, gypsum should be applied so that soluble salts released during dissolution do not negatively affect lettuce production. This probably can be accomplished by lengthening the time interval between application and planting.

Another interesting phenomenon concerning fertilizer management involves applying ammonia in irrigation water. Anhydrous ammonia raises the pH of irrigation water, causing the precipitation of $CaCO_3$, volatilization of NH_3 , and increased sodium hazard (Fig. 7). The simultaneous use of acid with anhydrous ammonia eliminates this problem.

Soil amendments and water treatments. Soil amendments and water treatments often offer a practical and economical means for managing many problems common to saline and sodic soils. Soil applications of amendments are used for initial reclamation and long-term maintenance of soil quality. In general, water applications are intended to alter the chemistry of irrigation water such that no further degradation in soil quality will occur. Rates of amendments used for soil application are typically large and primarily based on economics. For water treatments, rates of amendments are typically much smaller and are nearly always based on solubilities and stoichiometry.

Amendments such as gypsum and elemen-

tal S have been used for years. Gypsum is primarily used on Na-affected soils as a source of Ca^{2+} to displace Na^+ from the soil's colloidal exchange complex. The exchange flocculates soil particles (bunching of particles into larger aggregates). The Ca^{2+} ions reverse the effect of Na^+ ions, which tend to disperse soil particles and restrict water infiltration. The resulting displaced Na^+ ions are leached readily from the soil profile. Gypsum is a neutral salt that does not directly reduce pH. However, it can indirectly lower the pH of sodic soils by reducing the hydrolysis reactions associated with Na ions on the exchange complex. Gypsum often can reduce surface sealing and improve water infiltration in nonsodic soils by releasing electrolytes into percolating water (Ben-Hur et al., 1992; Shainberg et al., 1990; Warrington et al., 1989).

Elemental S is also a common soil amendment. Sulfur added to soil undergoes a slow biochemical oxidation to sulfuric acid. This affects the soil first by neutralizing soil bases and lowering pH directly, and second by dissolving native soil $CaCO_3$ to form gypsum, which then acts as described above. Iron pyrites also have been suggested as soil amendments (McGeorge and Breazeale, 1955). Like elemental S, iron pyrites oxidize to sulfuric acid (Banath and Holland, 1976).

Sulfuric acid often is applied to produce an effect more immediate than that produced by elemental S (Miyamoto et al., 1974; 1975a). Sulfuric acid can be added directly to the soil by specialized equipment or used as a water treatment. Studies in Arizona showed that water infiltration and seedling emergence were increased by gypsum, elemental S, or acid applied to the soil (McGeorge et al.,

Fig. 6. Chisel used routinely in the southwestern United States.

Fig. 7. Precipitation of carbonates in irrigation ditches after application of ammoniacal fertilizer. (Photograph courtesy of J. Stroehlein.)

1956). Because of the corrosive nature of sulfuric acid, other acid materials or acid-forming products have been used successfully as less hazardous substitutes. Acid or acid-forming amendments often are used to obtain the added benefit of enhanced P and micronutrient availability (Stroehlein and Pennington, 1986). Sulfuric acid and other acid-forming liquid materials have been highly effective when added to irrigation water as a water treatment (Stroehlein and Pennington, 1986; Yahia et al., 1976). Acid added to irrigation water not only improves infiltration by increasing the electrolyte concentration, but it reduces the carbonate and bicarbonate hazard of irrigation waters (Miyamoto et al., 1975b).

Calcium polysulfide and ammonium polysulfide also are used as water treatments to improve infiltration (Stroehlein and Pennington, 1986). These materials are initially basic and react to form colloidal S. The Ca^{2+} or ammonium (NH_4^+) ion can replace Na^+ on the exchange complex. Ammonium and S are then oxidized to form acid (H^+). Studies have shown improved infiltration with these products (El-Tayib et al., 1979; Cairns and Beaton, 1976). Not all of the beneficial effects can be attributed to S and ammonium oxidation. One field study in Arizona showed an immediate increase in infiltration before oxidation could occur (Stroehlein and Pennington, 1986), probably due to electrolyte effects.

Synthetic polymers were first investigated in the 1950s and 1960s. An extensive series of studies conducted in Arizona with polymers available at the time resulted in reduced soil compaction, improved stands, and increased yields compared

to untreated controls (Fuller et al., 1953). Although effective, most of these products evaluated in the 1950s and 1960s could not be used economically under field conditions.

Synthetic polymers such as polyacrylamide (PAM), polyvinyl alcohol (PVA), and polysaccharides have more recently shown promising results in research studies. Reduced soil surface crusting (Helalia and Lety, 1989; Terry and Nelson, 1986; Wood and Oster, 1985), improved aggregation and reduced clay dispersion (Aly and Lety, 1988), enhanced stand establishment (Cook and Nelson, 1986; Wallace and Wallace, 1986), reduced soil erosion with furrow and sprinkler irrigation (Ben Hur et al., 1990; Lentz et al., 1992; Levy et al., 1992), and improved reclamation of saline and sodic soils (Wallace et al., 1986) have been reported with the use of synthetic polymers.

Several studies in Israel and the United States showed improved infiltration with PAM and other polymers (Ben-Hur et al., 1989; Levy et al., 1992). In most of these studies slaking and dispersion were the dominant mechanisms limiting water intake. However, one study showed polymers to be effective in reducing clay swelling (Emerson, 1963). Shainberg et al. (1990) found that polymers increased water infiltration 3-fold over untreated soils. When gypsum was added with the polymer, infiltration increased another 3-fold over the polymer treatment alone.

Some researchers reported that synthetic polymers may be useful tools for managing and reclaiming sodic soils. Allison (1952) reported an increase in aggregate stability in several saline-sodic soils that were treated with polymers. Wallace et al. (1986) found that PAM added to a sodic soil improved soil aggregation, increased water penetration, and improved crop seedling emergence. Other researchers, however, found that polymers used alone were less effective in sodic soils. Aly

and Lety (1990) found that the stability of aggregates treated with polymers decreased as the soil SAR increased from 1 to 15. Zahow and Amrheim (1992) found increased hydraulic conductivity from polymer addition when the soil had an ESP <15, but found little or no increase when the soil ESP exceeded 15. However, these workers did find that synthetic polymers used in combination with gypsum increased hydraulic conductivity 4-fold over gypsum alone. These results underscore the need for a Ca source when reclaiming sodic soils and illustrate the apparent synergistic effects of gypsum and synthetic polymers.

Conclusions

Many economically important horticultural crops are sensitive to soil and water salinity and to the deterioration of soil physical properties associated with Na in soil and irrigation water. Therefore, soil chemical and physical properties, crop tolerance, water quality, fertilization, and irrigation method are important considerations for the production of horticultural crops. This is especially true in the southwestern United States, where warm winter temperatures favor production of many fruit and vegetable crops, but problems of salinity and sodicity are commonplace.

For purposes of organization we have outlined important considerations individually, but in reality they must be considered concurrently. Over the years, researchers have developed and calibrated a number of useful diagnostic and prognostic tools for dealing with salt and Na-related problems. Once problems (or the potential for problems) are identified, profitable production of horticultural crops depends on the selection of an economically viable management strategy. This may simply involve a minor, inexpensive modification of cultural practices under conditions of low to moderate salinity, or more costly reclamation under conditions of high Na.

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