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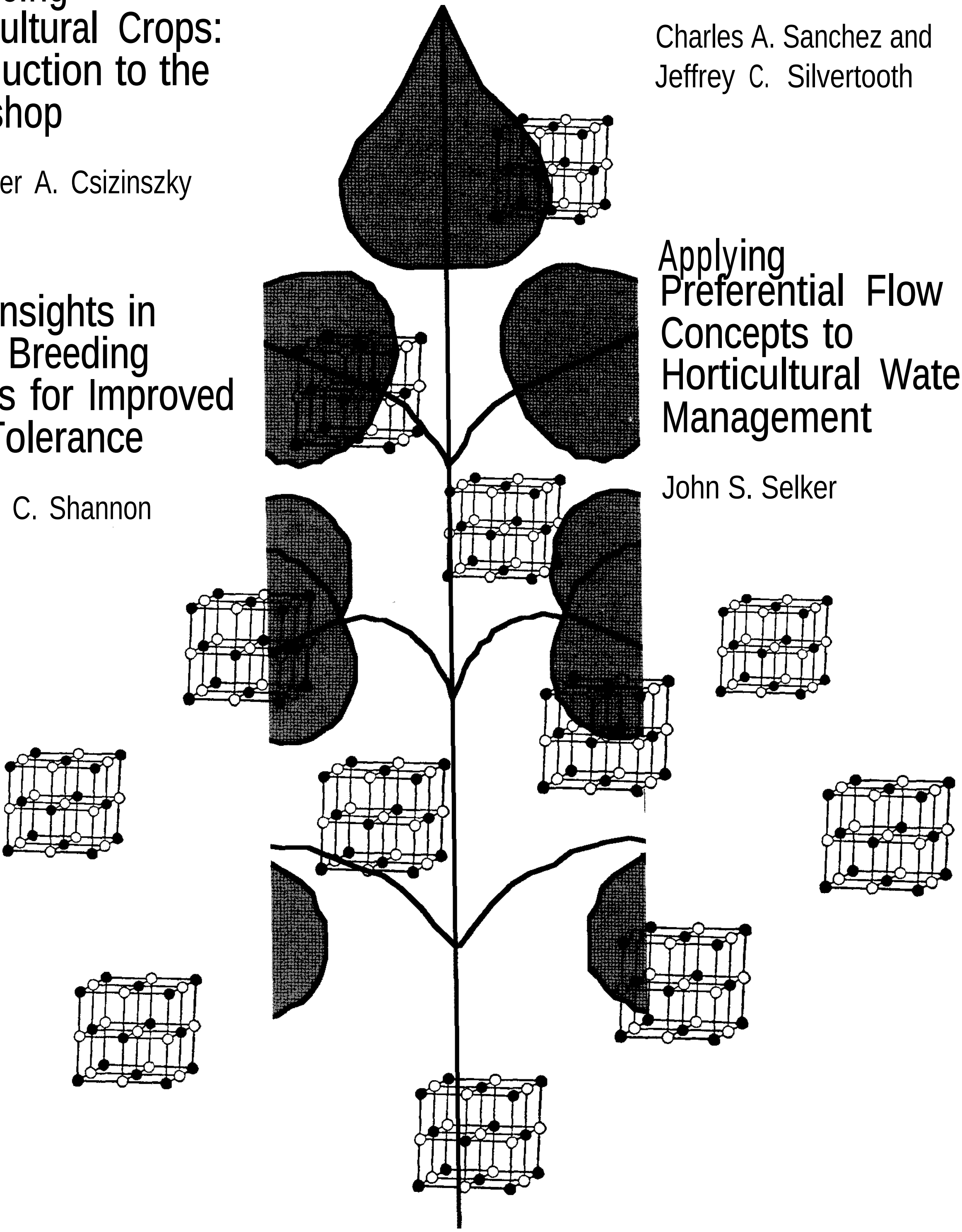

Considerations for Salt Management in Soil and Water for Producing Horticultural Crops: Introduction to the Workshop

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In nonhalophytic plants, saline conditions reduce vegetative growth and yields. Salt stress effects on plants from soil (≥ 4 dS·m^{-1} EC and <15% exchangeable Na+) or from saline (brackish) irrigation water (≥ 4 dS·m^{-1} EC) may be divided into three broad categories: 1) osmotic effects, 2) specific ion effects, and 3) interference with the uptake of essential nutrient ions (Hausenbuiller, 1972). Generally salts, once introduced, accumulate in the upper soil profile when they are transported by upward capillary movement of water, which evaporates, and when rainfall and irrigation are insufficient to leach salts to lower soil depths (Suarez, 1992). Thus, soil salinity is a particularly severe problem in the arid and semi-arid zones of the world or in areas where only poor-quality water is available for irrigation (Hamdy et al., 1993; Rowley, 1993; Satti et al., 1994). In the coastal areas of the United States, the gradual intrusion of seawater into the fresh-water aquifers threatens water supplies for agricultural, industrial, and municipal users (Cole, 1993).

Crops grown on saline soils or irrigated with salinewater requiredifferent management and irrigation methods than plants in nonsaline soils or irrigated with good-quality water. For example, in soils that have >15% exchangeable Na+, plants require soluble Ca^{2+} fertilizers to remedy ionic imbalances, which adversely affect their growth and development. Selecting crops and cultivars that can tolerate saline conditions and may produce economically acceptable yields is very important. Plants in the same family, or even the same species, react differently to saline conditions. For example, in Cruciferae, the order from highest to lowest tolerance to balanced fertilizer salts was cabbage>cauliflower > broccoli > kohlrabi (Csizinszky, 1979), and, in Leguminosae, the order was green pea > faba bean > soybean > green bean (Delgado et al., 1994). In Solanaceae, differences to salt stress among tomato cultivars were reported by Perez-Alfocea et al. (1993) and among eggplant cultivars by Zurayk et al. (1993).

Many plants have salt-sensitive stages during theirdevelopmentwhenirrigation bysainewatershould beavoided.Germinatingseedsandyoungseedlingsare particularly sensitive to salt stress, and irrigation with saline water during thesestages is harmful. Hamdyetal. (1993)recommended irrigationwith good-qualitywater during the salt-sensitive stages of growth, followed by saline water during later growth stages, when good-quality water may be scarce for irrigation purposes.

Althoughconsumptiveuseofwaterbyagriculture and industry has declined since the mid-1980s the demand for food, water, and land by an ever-growing population has increased (Solley, 1993; Suarez, 1992). Under these conditions, the knowledgeofcropmanagement on marginal lands, an understanding of irrigation management with brackish water, and crop selection for saline environmental conditions will increase in importance for horticulturists.

In the following articles, some soil and crop management methods, breeding and selecting plants for salt tolerance, and aspects of water and solute transport in soils are discussed.

Literature Cited

Co/e, J. 1993. Plenty of water but less to use. The Packer 100(34):A1.

Csizinszky, A.A. 1979. Effect of salt on seed germination and transplant survival of vegetable crops. Fla. Sci. 42:43-51.

Delgado, M.J., F. Ligero, and C. Lluch. 1994. Effects of salt stress on growth and nitrogen fixation by pea, faba bean, common bean and soybean plants. Soil Biol. Biochem. 26:371-376.

Hamdy, A., S. Abdel-Dayem, and M. Abu-Zeid, 1993. Saline water management for optimum crop production. Agr. Water Mgt. 24:189-203.

Hausenbuiller, R.L 1972. Soil science, principles and practices. W.M. Brown and Co., Dubuque, Iowa.

Perez-Alfocea, F., M. T. Estan, M. Caro, and M. C. Bolarin. 1993. Response of tomato cultivars to salinity. Plant Soil 150:203-211.

Rowley, G. 7993. Multinational and national competition for water in the Middle East: Towards the deepening crisis. J. Environ. Mgt. 39:187-197.

Satti, S.M.E.. M. Lopez, and F.A. Al-Said. 1994. Salinity induced changes in the vegetative and reproductive growth in tomato. Commun. Soil Sci. Plant Anal. 25:501-510.

Sol/ey, W.B. 7993. Water-use trends and distribution in theUnitedStates, 1950-1985. HortScience28:283-285.

Suarez, D. 1992. Perspective on irrigation management and salinity. Outlook Agr. 21:287-291.

Zurayk, R., M. Nimah, and M. Hamze. 1993. The salt tolerancepotential of localcultivarsofeggplant *(Solanum melongena* L.). Biol. Agr. Hort. 9:317-324.

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New Insights in Plant Breeding Efforts for Improved Salt Tolerance

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Additional index words. salinity, management, irrigation, genetic selection, systems research

Summary. The lack of improvement for salt tolerance has been attributed to insufficient genetic variation, a need for rapid and reliable genetic markers for screening, and the complexities of salinity x environment interactions. Salt tolerance is a quantitative characteristic that has been defined in many ways subject to changes with plant development and differentiation; thus, assessing salt tolerance among genotypes that differ in growth or development rate is difficult. Salt tolerance also varies based on concentrations of major and minor nutrients in the root zone. Plant growth models may provide a method to integrate the complexities of plant responses to salinity stress with the relevant environmental variables that interact with the measurement of tolerance. Mechanistic models have been developed over the last few years that are responsive to nitrogen or drought stress but not to salinity stress. Models responsive to salinity stress would provide insights for breeders and aid in developing more practical research on the physiological mechanisms of plant salt tolerance.

Salinity reduces yield and diminishes quality in fruit and vegetables. Historically, efforts to manage high salinity in soil or water has been through crop substitution and agromanagement. Crop substitution, or replacing salt-sensitive crops with more tolerant ones, has been practiced from the dawn of agriculture (Shannon, 1987) and is still probably one of easiest and most practiced strategies for

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dealing with salinity. When high-quality water is not available for irrigation and leaching, crop substitution has been the main approach to dealing with salinity. More salt-tolerant crops are substituted for salt-sensitive species. Thus, barley may be substituted for wheat, cotton for corn, sugar beet for lettuce, etc. Unfortunately, most vegetable crops are more sensitive to salt than most field crops. Harvest quality usually has a more significant impact on marketable yield of horticultural crops than field crops. The salt-tolerance tables developed by the U.S. Salinity Laboratory have been valuable guides for extension personnel and growers in determining which crops can be grown based on the expected soil salinity (Maas, 1990; Maas and Hoffman, 1977).

Agromanagement techniques that minimize and avoid salinity effects include leaching, deep plowing, applying amendment and carefully choosing fertilizer sources, installing drainage, land leveling, and irrigation technologies. Other management options include using drip or sprinkler irrigation to improve water application efficiency and elaborations in bed formation and planting design to facilitate removal of accumulated salts from the areas in which roots are developing and extracting water (Rhoades, 1993). Some strategies that have not been adequately researched involve manipulating population densities to improve plant stand and applying nonsaline or more saline water dependent on variable salt tolerance with growth stage.

More recently, crop breeding and genetic manipulation, using tools such as tissue culture and molecular biology, have been proposed as adjunct strategies to deal with salinity. Past work has shown that different crop species vary with respect to at least two of their parameters of salt tolerance-the salt tolerance threshold and yield decline beyond that threshold (Maas and Hoffman, 1977). These parameters reflect the simplest way to conceptualize the effects of salt on yield.

In the last 2 decades there has been great interest in breeding plants for improved salt tolerance (Shannon, 1979; Shannon and Noble, 1990). Strategies that have been tried or suggested include conventional screening, selecting and breeding with established cultivars, introducing high salt tolerance in cultivated species through introgression with tolerant wild relatives, or domesticating salt-tolerant wild or halophytic species through the genetic improvement of agronomic or horticultural characteristics. Some of these efforts have resulted in limited success but major advances have not been noted.

Examples of screening or selection criteria that have been tried include selection during germination or emergence, resistance to salinity-induced reductions in plant height or weight, and maintenance of high yield or quality under salt stress and plant survival (Shannon and Noble, 1990). Extensive efforts have also been made to identify reliable physiological or biochemical markers for salt tolerance. These markers include exclusion of ions (Na, Cl) from shoots or specific tissues, maintenance of nutrients (K, Ca, Mg, P, NO,), and ion selectivity (high K/Na,Ca/Na, or NO_3/Cl ratios) (Cheeseman, 1988; Jeschke, 1984; Shannon, 1979, 1982). Accumulated metabolic-compatible solutes such as proline, glycinebetaine, and certain sugars and alcohols have also been proposed as indices for high salt tolerance, but the evidence that accumulation of compatible solutes offers a quantitatively measurable improvement in salt tolerance has not been universally accepted

Physiologists have offered even more complex criteria for salt tolerance. Some of these include the ability of some species or varieties to maintain membrane integrity due to component structure or the ability to sequester ions via compartmentation, excrete ions through salt glands, or dilute ions using succulence (Lüttge and Smith, 1984; Thomsom et al., 1988). Some proposed morphological adaptations for salt tolerance include change in root-to-shoot ratio, rosette growth, succulence, reduction of stature through shoot or tiller abortion, and early initiation of reproductive growth (Läuchli and Epstein, 1990; Maas and Grieve, 1990; Maas and Nieman, 1978). Metabolic adaptations that have been associated with tolerance include increased respiration and improved water use efficiency at low salinity levels, increased mesophyll resistance, decreased CO, fixation, synthesis of compatible organic solutes, and the initiation of CAM metabolism (Lüttge and Smith, 1984;Shannon et al., 1994). It may not be obvious, but reduced growth rate, in itself, may be an adaptation to high salinity. A smaller plant requires less water and does not concentrate excluded salts in the root zone to the same extent as a plant that maintains a more rapid growth rate.

At least three dogmas have been established with respect to salinity stress. First, salinity is a multicomponent stress in a physical and chemical sense and varies in intensity over the three dimensions of space, time, and concentration. Its effects depend on specific salt composition and are subject to environmental interactions. The second dogma is that within the plant kingdom there exists a vast array of adaptive responses to salinity stresses. The physiological significance or quantitative importance of most of these has not been explicitly proven or quantitatively described and will continue to be a major research objective. A third well-known dogma is that salinity stress is highly sensitive to interactions with other environmental variables, especially humidity and light intensities (Magistad et al., 1943; Salim, 1989).

The complexities intertwined in the aforementioned dogmas highlight the need for a method of conceptual integration. Within the last 50 years much information has been developed concerning salt tolerance and effects of salinity on plants or plant components. However, the component observations and facts constitute a hodgepodge that resists comprehension. A new impetus is needed to advance breeding for salt tolerance to a higher level. Two technologies that will be useful in the breeding effort are crop modeling and systems methodology. Process-based plant growth models help simulate complex crop responses to salinity in an integrative manner over different growth stages and soil-environment scenarios. Although mechanistic models responsive to salinity stress are just beginning to be developed, there is reasonable hope that such models will soon provide a new basis for testing hypotheses and experimental design. Most existing plant growth models treat the soil simplistically. Integrated soil chemistry and physics models that describe water movement and chemical interactions are available (Simunek et al., 1992; Suarez and Simunek, 1994) but these models treat the plant in a simplistic manner and incorporate the effects of salinity through empirical rather than mechanistic relationships. These models oversimplify calculations for yield and root water uptake. Second-generation models that address and correct some of these problems are currently being developed. These models will be developed to handle salinity stress in a more mechanistic and comprehensive manner, including differential salt sensitivity relative to growth stage and a better coupling of growth and root water uptake with above-ground plant growth and development.

Systems approaches also provide an opportunity to coalesce and use efficiently available technology and the accumulated knowledge concerning salt tolerance that has been obtained in the last 2 decades (Shannon, 1994; Wymore, 1993). System approaches as applied to the development of salt tolerance include the following:

1) Defining the problem;
2) Establishing inputs and outputs;
3) Identifying requirements for performance and resource use;
4) Assessing available technology;
5) Developing a solution concept; and
6) Developing screening and selection procedures that will lead to a plant ideotype to fit the prescribed requirements of the agronomic system.

The problem to be defined is the specific salinity problem that is being addressed in the context of crop species, agricultural environment, and specific ion and toxicity thresholds during cropping. This requires significant input from growers and produce buyers. A description of the salinity situation should include source of salinity (e.g., irrigation water, soil, water table), salt-specific ion distribution and concentration information, and environmental factors such as range of affected crop land, climate, soil type, and drainage availability.

Genetic variability should be assessed to determine the extent to which cultivars express a salt tolerance that might prove useful for the problem being considered. This assessment should include the known salinity threshold, yield decline parameters for the crop, and information on intervarietal and interspecific variability. Also, information should be collected on known interactions among salinity responses and other environmental variables. Available physiological or morphological mechanisms with importance for salt tolerance should be noted.

Accurately defining the problem is essential for establishing input and output requirements. Assessments should be made with regard to the economic situation and genetic variability. The economic situation should be appraised with consideration to costs to the grower, such as seed, water fertilizer, chemicals, field operations, fuel, labor, and overhead. Such costs should beweighed against market considerations (e.g., yield, quality, earliness), allotments and price supports, and indirect effects, such as long range sustainability or potential of using and generating saline drainage or groundwater.

Performance and resource use requirements must be identified at this juncture. Crop yield and quality requirements should be defined and fixed costs for production should be specified. Managementoptionsshould beweighed against breeding potential. If management is a relatively inexpensive input into the system, then perhaps a full-scale breeding effort is not needed. If using saline water is a requirement, adequate genetic variability must be potentially available to produce a crop that is economically successful. For efforts that require management and breeding, for example, tolerance at specific growth stages should be identified. The magnitude of increase in salt tolerance needed to achieve success should be identified.

Available **technology** must be assessed to determine the types of germplasm and equipment that are available. Salt-tolerant rootstocks have been identified for a number of woody species, including citrus, grape, avocado, and stonefruits (Maas, 1986). Cultivars of lettuce, tomato, melon, and several other crops that have greater relative salt tolerances than others have been identified (Shannon and Francois, 1978; Shannon and Noble, 1990; Shannon et al., 1983). In some instances, a closely related salt-tolerant species might be useful in place of a more sensitive species; for instance, cantaloupe might be used instead of watermelon, or a salt-tolerant forage such as tall wheatgrass or subterranean clover might replace crested wheatgrass or white clover(Shannon, 1978; Shannon and Noble, 1995). Salt-tolerant lines may be incorporated into the overall strategy as substitutes for sensitive cultivars or species or as potential parents in a crossing and selection program designed to achieve greater salt tolerance.

The next step is to *develop a solution concept.* The essence of this is to develop a functional conceptual model of the plant ideotype that will fill the niche in a described agromanagement system, a system that will fulfill all of the established requirements. Crop growth simulation models may someday be useful in hypothesis testing of such ideotypes before screening and selection technologies are used in a full-scale breeding program.

The concept of the ideotype can be used to *develop screening and selection procedures* Thescreening program may be focused on a selected combination of physiological and morphological characters that are predicted to best fit a proposed management system in the target environment. Any combination of technologies from conventional breeding to molecular approaches might be used to achieve the desired ideotype. After the desired genotype is obtained through any procedure, it is important that procedures be established for germplasm maintenanceand protection and future varietal improvement and development. Otherwise, the unique combinations that infer salt tolerance with the specific target environment cannot be expected to endure growth stages (Shannon, 1985).

Many successful plant breeders are able to conceptualize intuitively the steps that have been outlined herein to produce successful cultivars in nonsaline situations; however, salinity problems associated with irrigated agriculture are complex and require a more rigorous and structured effort. The lack of such a structured effort has contributed as much to the lack of progress in breeding for salt tolerance as have previous gaps in information concerning salt tolerance mechanisms.

Literature Cited

Cheeseman, J.M. 1988. Mechanism of salinity tolerance in plants. Plant Physiol. 87:547-550.

Jeschke, W.D. 1984. K+-Na+ exchange at the cellular membranes, intercellular compartmentation of cations and salt tolerance, p. 37-66. In: R.C. Staples and G.H. Toenniessen. (eds.). Salinity tolerance in plants: Strategies for crop improvement. Wiley, New York.

Läuchli, A. and E Epstein. 1990. Plant responses to salineand sodicconditions, p, 113-137. In: K.K. Tanji. (ed.). Agricultural salinity assessment and management. Amer. Soc. Civil Eng. Manuals Rpt. Eng. PracticeNo.71, Amer. Soc Civil Eng., New York.

Lüttge, U. and J.A.C. Smith. 7984. Structural, biophysical, and biochemical aspects of the role of leaves in plant adaptation to salinity and water stress, p. 125-150. In: R.C. Staples and G.H. Toenniessen. (eds.). Salinity tolerance in plants: Strategiesforcrop improvement. Wiley, NewYork.

Maas, E V. 1986. Salt tolerance of plants. Appl. Agr. Res. 1:12-26.

Maas, E V. 1990. Crop salt tolerance, p. 262-304. In: K.K. Tanji. (ed.). Agricultural salinity assessment and management. Amer. Soc. Civil Eng. Manuals Rpt. Eng. Practice No. 71. Amer. Soc. Civil Eng., New York.

Maas, E. V. and C.M. Grieve. 1990. Spike and leaf development in salt-stressed wheat. Crop Sci. 30:1309-1313.

Maas, E.V. and G.J. Hoffman. 1977. Crop salt tolerance-Current assessment. J. Irr. Drainage Div., Amer. Soc. Civil Eng. 103(IR2):115-134.

Maas, E. V.and R.H. Nieman. 1978. Physiology of plant tolerance to salinity. In:G.A.Jung(ed.). Crop tolerance to suboptimal land conditions.ASASpec. Publ. 32:277-299.

Magistad, O.C., A.D. Ayers, C.H. Wadleigh, and H.G. Gauch. 7943. Effect of salt concentration, kind of salt, and climate on plant growth in sand cultures. Plant Physiol. 18:151-166.

Rhoades,J.D. 1993,Practices to control salinity in irrigated soils, p. 379-387. In: H. Lieth and A. Al Massoum (eds.). Towards tational use of high salinity tolerant plants. vol 2. Proc. 1st ASWAS Conf. 8-15 Dec. 1990, Al Ain Univ, United Arab Emirates, Kluwer Acad. Publ., Dordrecht.

Salim, M. 1989. Effects of salinity and relative humidity on growth and ionic relations of plants. New Phytol. 113:13-20.

Shannon, M.C. 1978. Testing salt tolerance variability among tall wheatgrass lines. Agron. J. 70:719-722.

Shannon, M.C. 1979. In quest of rapid screening techniques for plant salt tolerance. Hort Science 14:587-589.

Shannon. M.C. 7982. Genetics of salt tolerance: New challenges, p, 271-282. In: A. San Pietro (ed.). Biosaline research: A look into the future. Plenum Publ. Corp.

Shannon, M. C., J. D. McCreight, and J. H. Draper. 1983. Screening tests for salt tolerance in lettuce. J. Amer. Soc. Hort. Sci. 108:225-230.

Shannon. M.C. 1985. Principles and strategies in breeding for higher salt tolerance. Plant Soil 89:227-241.

Shannon, M.C. 1987. Salinity-An environmental constraint on crop productivity, p. 9-18. 4th Austral. Agron. Soc. Conf., Responding to Change, La Trobe, Univ., Melbourne,Australia,24-27Aug.

Shannon, M.C. 1994. Development of salt stress tolerance-Screening and selection systems for genetic improvement, p. 117-332.In:V.C. Baligar, R.R. Duncan, and J. Maranville(eds.). Proc. Workshop on Adaptation of Plants to Soil Stresses, Sorghum and Millet Collaborative Support Program (INTSORMIL), Univ. of Nebraska, l-4 Aug. *1993.*

Shannon, M.C. and L.E. Francois. 1978. Salt tolerance of three muskmelon cultivars. J.Amer.Soc. Hort. Sci. 103:127-130.

Shannon, M. C., C. M. Grieve, and L.E Francois. 1994. Whole plant response to salinity, p. 199-244. In: R. E. Wilkinson (ed.). Plant response mechanisms to the environment, Marcel Dekker, New York.

Shannon, M.C. and C.L. Noble. 1990. Genetic approaches for developing economic salt-tolerant crops, p. 161-185. In: K.K. Tanji. (ed.). Agricultural salinityassessmentand management. Amer. Soc. Civil Eng. Manuals Rpt. Eng. Practice No. 71. Amer. Soc. Civil Eng., New York.

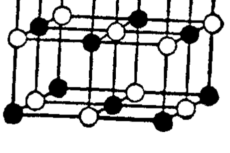
Shannon, M. C. and C. L Noble. 1995. Variation in salt tolerance and ion accumulation among subterranean clover cultivars. Crop Sci. 35:798-804.

Simunek, J., T Vogel, and M. Th. van Genuchten. 1992. The SWMS_2 code for simulating water flow and solute transport in two-dimensional variably saturated media. version 1.1. Res. Rpt. No. 126, U.S. Salinity Lab., Riverside, Calif.

Suarez, D.L. and J. Simunek. 1994. Modeling equilibrium and kinetic major ion chemistry with CO, production/transport coupled to unsaturated water flow, p. 1215-1246. In: Gee and N.R. Wing (eds.). *In situ* remediation: Scientific basis for current and future technologies. Part 2, G.W. 33rd Hanford Symp. on Health and the Environment, Pasco, Wash.

Thomson, W.W. CD. Faraday, and J. W. Oross. 1988. Salt glands, p. 498-537. In: D.A. Baker and J.L. Hall (eds.). Solute transport in plant cells and tissues. Longman Scientific &Technical, Harlow, Essex, England.

Wymore, A. W. 1993. Model-based systems engineering. CRC Press, Boca Raton, Fla.



Managing Saline and Sodic Soils for Producing Horticultural Crops

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Additional index words. irrigation, water quality, salt tolerance, soil amendments, soil analysis

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 $dS\cdot m^{-1}$ is considered saline, but some horticultural crops are negatively affected if salt concentrations in the rooting zone exceed 2 $dS\cdot m^{-1}$. 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.

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 $dS\cdot m^{-1}$ (Table 1). However, many salt-sensitive horticultural crops, such as lettuce (*Lactuca sativa* L.), are harmed by EC_e >2 $dS\cdot m^{-1}$.

Sodicity refers to an excess of exchangeable Na in the soil. In addition to direct toxic affects 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.

$$SAR_e = (Na)/((Ca + Mg)/2)^{0.5} \qquad [1]$$

where concentrations are expressed in meq/liter.

Although SAR_e has a chemical basis in the

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

Criterion	Normal	Saline	Sodic	Saline-Sodic
EC, (dS·m^{-1})	**<4**	**>4**	**<4**	**>4**
SAR,	<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, (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, ratio, which is only empirically related to SAR, and ESP. Statistical relationships derived from several soils indicate that practical SAR, values are about 12% < SAR, values and reasonably close to ESP values (Sposito and Mattigod, 1977). Hence, soils with practical SAR, 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. Forexample, consider a sand,a loam,and a muck soil all having an EC, of 2 dS·m^{-1} and containing 24%, 40%, and 150% moisture at saturation, respectively(Table2). 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 22 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:fieldcapacitymoisture, tocorrect 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 recently, as part of a research program directed toward developing technologies for measuring in situ bulk soil salinity (EC,), more accurate models have been developed that interrelate EC$_a$ and EC, based on selected soil properties (Rhoades 1981; Rhoades et al., 1989a, 1989b,1990).

Spatial variability The salt and Na status of afield typically is determined from a composite soil sample. However, such a protocol ignores variation in salinityacrossagivenfield. Managing 10- to 20-ha units based on a composite soil sample mightaffectsalt-sensitivecropsadversely. Note the variation in EC, 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, measurement is generally impractical. However, field determination of soil-paste electrical conductivities (EC,) (Rhoades et al. 1989a) andfieldmeasurementsofbulksoil salinity (EC,) using four electrode sensors, electromagnetic measurements, or time domain reflectometric sensors show promise as apractical meansofassessingfield 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 notamajorproblematpresent. 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 plants 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 establishedfor 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, 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)attestto 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

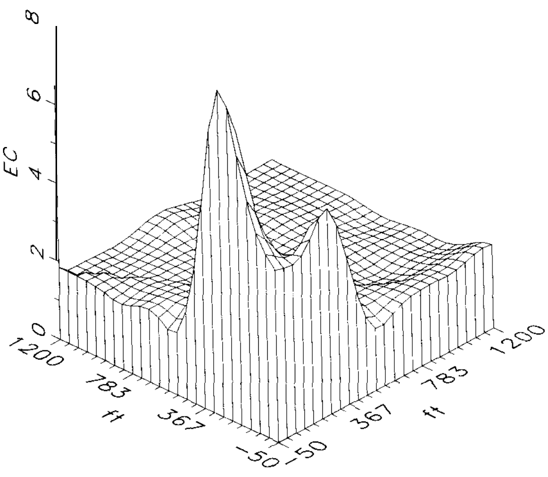

Fig. 1. *Variability in soil EC, values in a field in southwestern Arizona (Yuma Valley) before lettuce seeding. (Unpublished data provided by Agro Phosphate Inc.)*

Table 3. ***Yield potential of selected vegetable and fruit crops^z as influenced by soil salinity (EC$_e$).***

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

[z] Adapted 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 measurements. Based on statistical relationships developed from several waters, total dissolved solids (TDS mg·liter^{-1}) can be estimated by multiplying EC, (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,). 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 (CO_3^{2-}) and bicarbonate (HCO_3^-) 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):

$$RSC = [HCO_3^- + CO_3^{2-}] - [Ca^{2+} + Mg^{2+}] \qquad [2]$$

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 HCO_3^- 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-

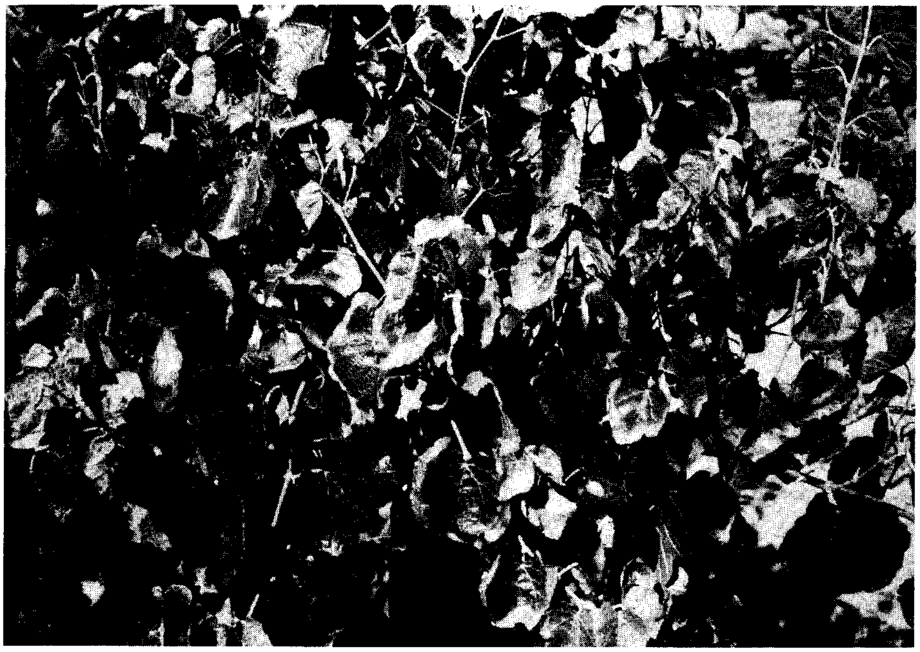

Fig. 2. *Chloride toxicity to furrow-irrigated grapes near Safford, Ariz. (Photograph courtesy of T. Doerge.)*

Table 4. *Tolerance of citurs rootstocks to chloride in soil* **(Cl_e)** *and irrigation* **water.**[z]

Rootstock	Soil (Cl,)	Irrigation water (Cl,)
	meq/liter	
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		

'Adapted from Maas (1984).

cause it issimpler and moreaccurate than alternative procedures. This equation is discussed in moredetail belowwith respectto 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 $dS\cdot m^{-1}$. 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 bedshapeandplantingarrangementarestrategies 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 asteady-stateassumption of mass balance and are calculated by

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

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,, 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 conditions, 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, 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 Langliers's index to include empirically derivedparametersaimedatpredicting 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; Osterand Rhoades, 1975), thus limiting its

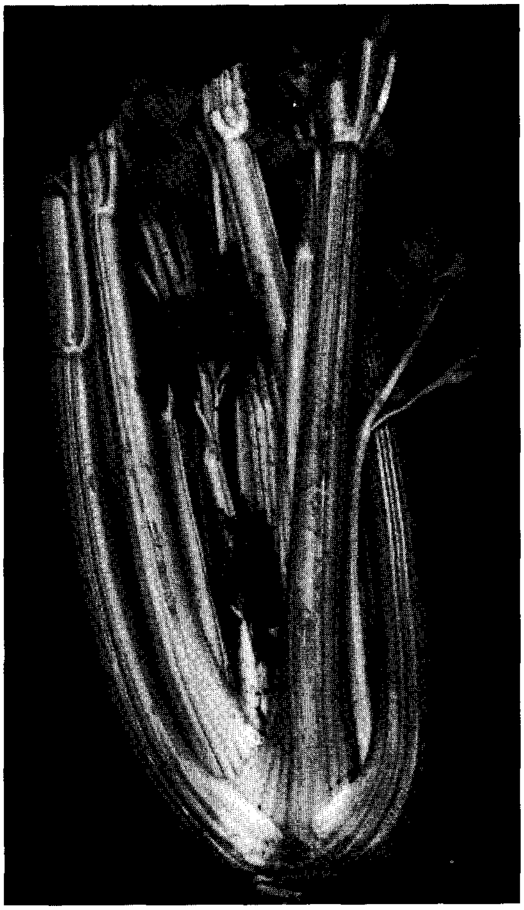

Fig. 3. *Celery blackheart, a calcium-related physiologicaldisorder. In this case blackheart was caused by a high concentration of monovalent salts in the rooting zone.*

predictive potential. Suarez (1981) proposed the following:

$$\text{Adj SAR}_{dw} = (Na_{iw}/LF)/\{(Mg_{iw}/LF + X(P_{CO2})^{1/3}\}^{1/2} \quad [4]$$

where Na_{iw} and Mg_{iw} are the concentrations of Na and Mg in irrigation water as mmol·liter^{-1}, P_{CO2} is the partial pressure of CO, 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_{CO2}, 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

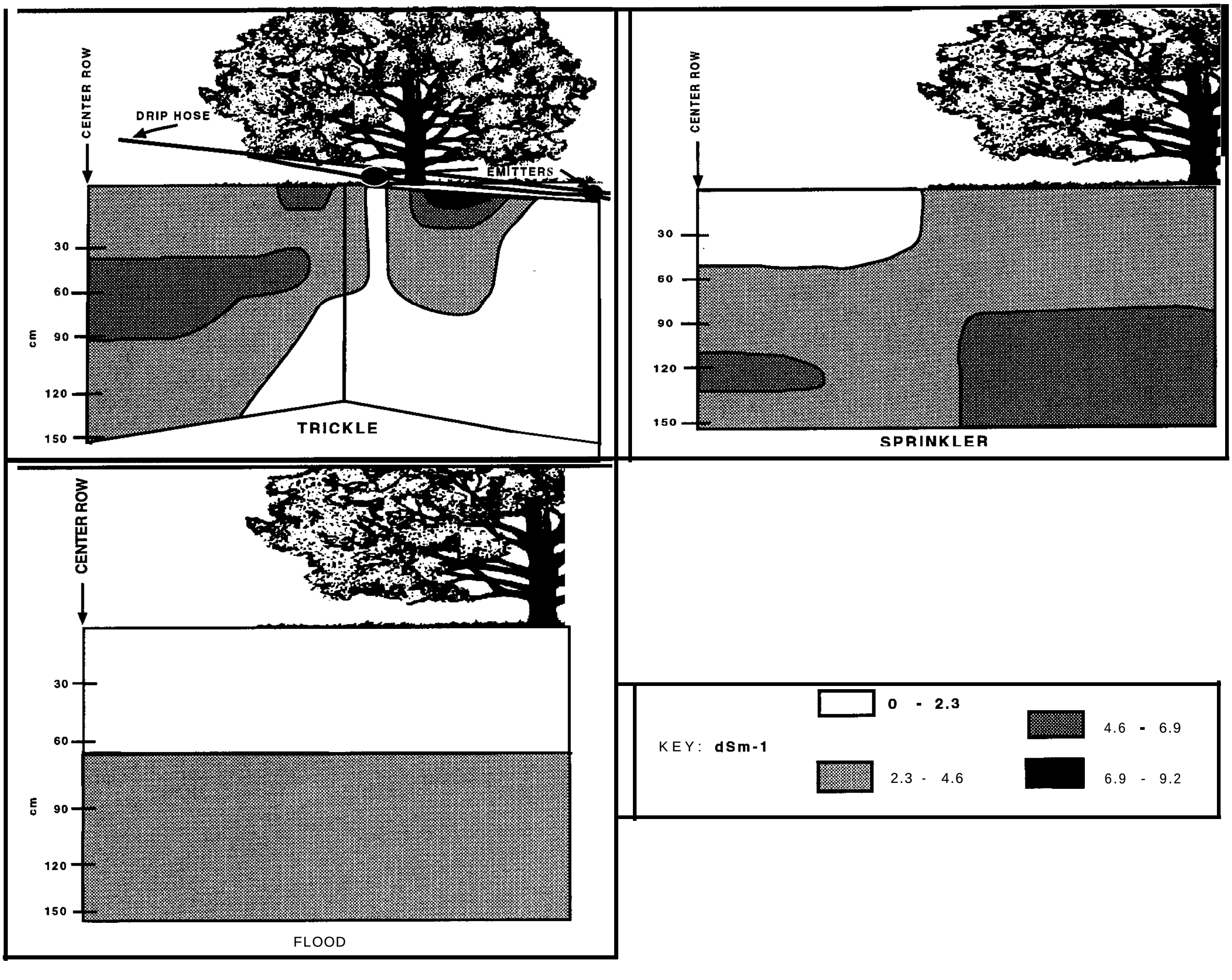

Fig. 4. *Salt distribution patterns below a 'Valencia' orange grove in southwestern Arizona (Wellton Mesa) as influenced bv irrigation system. (Unpublished data provided by R. Roth.)*

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.G. 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 elemental 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.*

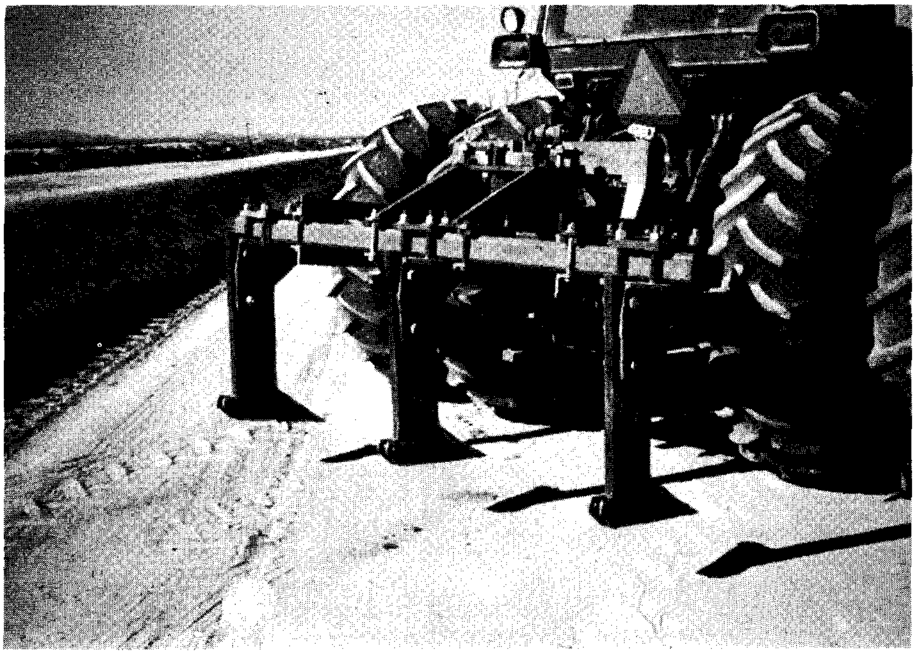

Fig. 7. *Precipitation of carbonates in irrigation ditches after application of ammoniacal fertilizer. (Photograph courtesy of J. Stroehlein.)*

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 Letey, 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.

Literature Cited

Allison, L.E. 1952. Effect of synthetic polyelectrolytes on the structure of saline and alkali soils. Soil Sci. 73:443454.

Aly, SM. and J. Letey. 7988. Polymer and water quality effects on the flocculation of montmorillonite. Soil Sci. Soc. Amer. J. 52:1453-1458.

Aly, SM. and J. Letey. 1990. Physical properties of sodium treated soil as affected by two polymers. Soil Sci. Soc. Amer. J. 54:501-504.

Ayers, RS. and D. W. Westcot. 1989. Water quality for agriculture. FAO Irr. Drainage Paper 29.

Banath, *CL. and JF Holland. 1976.* Iron pyrites as a sulfur fertilizer in an alkaline soil. Austral. J. Agr. Animal Husb. 16:376-381.

Ben-Hur, M., J. Faris, M. Malik, and J. Lety. 1989. Polymers as soil conditioners under consecutive irrigations and rainfall. Soil Sci. Soc. Amer. J. 53:1173-1177.

Ben Hur, M., J. Lety, and I. Shainberg. 1990. Polymer effects on erosion under laboratory rainfall simulator conditions. Soil Sci. Soc. Amer. J. 54:1092-1095.

Ben-Hur, M., R. Stern, A.J. van der Merwe, and I. Shainberg. 1992. Slope and gypsum effects on infiltration and erodability of dispersive and nondispersive soils. Soil Sci. Soc. Amer. J. 56:1571-1576.

Bernstein, L. 1964. Salt tolerance of plants. U.S. Dept. of Agr. Info. Bul. 283.

Bernstein, L 1965. Salt tolerance of fruit crops. U.S. Dept. of Agr. Info. Bul. 292.

Bernstein, L. 1974. Crop growthandsalinity. In: J. van Schilfgaarde (ed.). Drainage for agriculture. Agronomy 17:39-56..

Bernstein, L and M. Fireman. 1957. Laboratory studies on salt distribution in furrow irrigated soil with special reference to pre-emergence period. Soil Sci. 83:249-263.

Bernstein L and L.E. Francois. 1973. Comparisons of drip, furrow, and sprinkler irrigation. Soil Sci. 115:73-86.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1985. Soil chemistry. 2nd ed. Wiley, New York.

Bohrer, V.L. 1970. Ethnobotanical aspects of Snaketown, a Hohokam village in southern Arizona. Amer. Antiquity 35:413-430.

Bower, C.A., G. Ogata, and J.M. Tucker. 1968. Sodium hazard of irrigation waters as influenced by leaching fraction and by precipitation or solution of calcium carbonate. Soil Sci. 106:29-34.

Cairns, R.R., and J.D. Beaton. 1976. Improving a solonetzic soil by nitrogen-sulfur materials. Sulfur Inst. J. 12:10-12.

Cook, D.F. and S.D. Nelson. 1986. Effect of polyacrylamide on seedling emergence in crust-forming soils. Soil Sci. 141:328-333.

El-Tayib, YM,, J. Lety, and R. Branson. 1979. Sulfur compounds in water treatment-effect on infiltration rate. Sulfur 3:7-11.

Eaton, F.M. 1944. Deficiency, toxicity, and accumulation of boron in plants. J. Agr. Res. 69:237-277.

Eaton, F.M. 1950. Significance of carbonates in irrigation waters. Soil Sci. 69:123-133.

Emerson, W. W. 1963. The effect of polymers on the swelling of montmorillonite. J. Soil Sci. 14:52-63.

Francois, L.E. 1995. Salinity effects on bud yield and vegetative growth of artichoke *(Cynara scolymus* L.). HortScience 30:69-71.

Fuller, W. H., N. V. Gomness, and L V. Sherwood. 1953. The influence of soil aggregate stabilizers on stand, composition, and yield of crops on calcareous soils of southern Arizona. Univ. Arizona Tech. Bul. 129.

Hammond, L.C. 1966. Soil-water-salinity-plant relationships, Proc. Soil and Crop Sci. Soc. Fla. 26:257-264.

Harding, R. B., M. P. Miller, and M. Fireman. 1958. Absorption of salts by citrus leaves during sprinkling with water suitable for surface irrigation. Proc. Amer. Soc. Hort. Sci. 71:248-256.

Hartz, TK 1994 Minimizing environmental stress in field establishment ofvegetablecrops in the southwestern United States. HortTechnology 4:29-34.

Helalia, A. M. and J. Letey. 1989. Effects of different polymers on seedling emergence, aggregate stability, and crust hardness. Soil Sci. 148:199-203.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992 Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Amer. J. 56:1926-1932.

Lesch, SM., J.D. Rhoades, L.J. Lund, and D.L. Corwin. 1992. Mapping salinity using calibrated electromagnetic measurements.. Soil Sci. Soc. Amer. J. 56:540-548.

Levy, G.J, J. Levin, M Gal, M Ben-Hur, and I. Shainberg. 7992. Polymers' effects on infiltration and soil erosion during consecutive simulated sprinkler irrigations. Soil Sci. Soc. Amer. J. 56:902-907.

Maas, E.V. 1984. Salt tolerance of plants. In: B.R. Christie (ed.). The handbook of plant science in agriculture. CRC Press, Boca Raton, Fla.

Maas, EV: and G.J. Hoffman. 1972 Crop salt tolerance-Current assessment. Amer. Soc. Civil Eng. Proc. J. Irr. Drainage. Div. 103:115-131.

McGeorge, W.T. and E.L. Breazeale. 1955. The value of pyrite and Pyrhotite as soil conditioners. Univ. Arizona Agr. Expt. Sta. Rpt. 124.

McGeorge, W. T., EL. Breazeale, and J. T. Abbott. 1956. Polysulfides as soil conditioners. Univ. Arizona. Bul. 131.

Miyamoto, S., H. L. Bohn, J. Ryan, and M.S. Yee. 1974. Effectsofsulfuricacidandsulfurdioxideon aggregate stability of calcareous soils. Soil Sci. 118:299-303.

Miyamoto, S, R.J. Prather, and J. L Stroehlein. 1975a. Sulfuric acid and leaching requirement for reclaiming sodium-affected soils. Plant Soil. 43:773-585.

Miyamoto, S., R.J. Prather, and J.L. Stroehlein. 1975b. Sulfuric acid for controlling calcite precipitation. Soil Sci. 120:264-271.

O'Connor, G.A. 1971. Testing sodium hazard predictions. Soil Sci. Soc. Amer. Proc. 35:510-512.

Oster, J.D. and J.D. Rhoades. 1975. Calculated drainage compositions and salt burdens resulting from irrigation with river waters in the western United States. J. Environ. Qual. 4:73-79.

Pearson. G.A. 1960. Tolerance of crops to exchangeable sodium. USDA Info. Bul 216.

Rader, L.F. 7943. Salt index for fertilizers. Soil Sci. 55:201-208.

Rhoades, J.D. 1968. Leaching requirement for exchangeable sodium control. Soil Sci. Soc. Amer. Proc. 32:652-656.

Rhoades, J,D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284.

Rhoades, J.D. 1981. Predicting bulk soil electrical conductivity versus saturation paste extract electrical conductivity calibrations from soil properties. Soil Sci. Soc. Amer. J. 45:42-44.

Rhoades, J.D. and J.D. Oster. 7986. Solute content, p, 985-1006. In: A. Klute (ed.). Methods of soil analysis. Part 1. 2nd ed. Monog 9. ASA and Soil Sci. Soc. Amer., Madison, Wis.

Rhoades, J. D., N.A. Manteghi, P. J. Shouse, and A.J. Alves. 1989a. Estimating soil salinity from saturated soil-paste electrical conductivity. Soil Sci. Soc. Amer. J. 53:428-433.

Rhoades, J. D., N.A. Manteghi, P.J. Shouse, and WJ. Alves. 1989b. Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Amer. J. 53:433-439.

Rhoades, J. D., P.J. Shouse, WJ. Alves, N.A.

Manteghi, *and S.M. Lesch. 1990.* Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Sci. Soc. Amer. J. 54:46-54.

Robinson, L.A. 1973. Increase in conductivity of irrigation water during sprinkling. Agron. J. 65:130.

Shainberg, I., D. N. Warrington, and P. Rengasanmy. 1990. Water quality and PAM interactions in reducing surface sealing. Soil Sci. 149:301-307.

Sposito, G. and S. V. Mattigod. 1977. On the chemical foundation of the sodium absorption ratio. Soil Sci. Soc. Amer. J. 41:323-329.

Stroehlein, J, L andD.A. Pennington. 1986. Use of sulfur compounds for soil and irrigation water treatments. Agronomy 27:435-454.

Suarez, D.L. 1987. Relationship between pH_c and sodium adsorption ratio (SAR) and an alternative method of estimating SAR of soil or drainage waters. Soil Sci. Soc. Amer. J. 45:469-475.

Terry, R.E and S.S. Nelson. 1986. Effects of polyacrylamide and irrigation method on soil physical properties. Soil Sci. 141:317-320.

Wallace, A. and G.A. Wallace. 1986 Effects of soil conditioners on emergence and growth of tomato, cotton, and lettuceseedlings. Soil Sci. 141:313-316.

Wallace, A, G.A. Wallace, and A.M. Abouzamam. 7986. Amelioration of sodic soils with polymers. Soil Sci. 141:359-362.

Warrington, D., I. Shainberg, M. Agassi, and J. Morin. 1989, Slope and phosphogypsum's effect on runoff and erosion. Soil Sci. Soc. Amer. J. 53:1201-1205.

Wilcox, L.V., G. Y Blair, and CA. Bower. 1954. Effect of bicarbonate on suitability of water for irrigation. Soil Sci. 77:259-266.

Wood, J.D. and J.D. Oster. 1985. The effect of cellulose xanthate and polyvinyl alcohol on infiltration, erosion, and crusting at different sodium levels. Soil Sci. 139:243-249.

Yahia, TA., S. Miyamoto, and J. L Stroehlein. 7975. Effect of surface applied sulfuric acid on water penetration into dry calcareous and sodic soils. Soil Sci. Soc. Amer. Proc. 39:1201-1204.

Yenson, N.P. and J.L. Bedell. 7993. Considerations for the selection, adaptation, and application of halophyte crops to highly saline desert environments as exemplified by the long-term development of cereal and forage cultivars of *Distichlis spp.* (Poaceae), p. 305-313. In: H. Leith and A. Al Masoom (ed.). Toward the rational use of high salinity tolerant plants. vol. 2. Kluwer Academic Publishers, The Netherlands.

Zahow, M.F. andC. Amrheim. 1992 Reclamation ofasalinesodicsoil usingsyntheticpolymersand gypsum. Soil Sci. Soc. Amer. J. 56:1257-1260.

Applying Preferential Flow Concepts to Horticultural Water Management

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Summary. Avoiding groundwater contamination from agricultural activities is possible only if the processes that control deep percolation are understood. The source of contaminant movement to groundwater is typically through preferential flow, processes by which the bulk soil is bypassed by some part of the infiltrating water. Three mechanisms give rise to preferential flow: fingered flow, funnel flow, and macropore flow. Fingered flow occurs in coarse-textured soils and can be minimized by starting with an initially well-wetted profile. Funnel flow is likely in layered soil profiles of silt or coarser-textured soil,.in which avoiding slow over-irrigation is critical. Macropore flow is observed in all structured soils in which maintaining irrigation rates well below the saturated conductivity of the soil is essential. These prescriptions are quite different than conventional recommendations, which fail to consider groundwater protection.

The quantitative study of the movement of water through soils is well over 100 years old (e.g., Lawes et al. 1882) and continues to be an area of active research. This interest generally stems from two concerns: 1) how to manage soil water to obtain the greatest crop response and production; and 2) how to minimize the impact of cropping activities on the environment.

Until the 1970s most of the research concerning soil water movement concentrated on attempts to predict flow in homogeneous soils (Gardner, 1958; Green and Ampt, 1911; Philip, 1969). This approach was used not because it was thought to be the most realistic representation of soils, but because it allowed the application of powerful mathematical tools to solve some fundamental problems. In the 1970s the first widespread observations of groundwater contamination were noted. Although the most famous of these cases (e.g., Love Canal) were due to industrial sources, agricultural activities also have been implicated. In many of these cases contamination would not have been predicted to reach the aquifer using models that assumed homogeneous soil and uniform water content. These realizations led to the development of more realistic and complete descriptions of solute movement through soils. The unaccounted for and widespread behavior of water moving unevenly through soil is described as preferential flow. These processes allow some of the infiltrating water to percolate more quickly than if the soil were uniformly carrying flow.

This article summarizes the research findings that explain these transport processes, providing horticulturists guidelines to enhance efficient use of water, increase efficiency of salinization control, and minimize groundwater contamination

Fingered flow

Hill and Parlange (1972) noted that in coarse-textured soils water tends to move in isolated regions, or fingers of flow. This process is recognized as an instability in the wetting front, analogous to the instability in the darting tongues of a flame, or the flapping of a flag. This process was soon put into the mathematical framework of linear instability theory (Parlange and Hill, 1976) which has since been shown to provide reasonable estimates of the physical dimensions (i.e., width) of these fingers of flow (Glass et al., 1989; Selker et al., 1992).

From a practical point of view, the fact that the width of fingers can be predicted is useful. It confirms that our conceptual model for fingered flow is capturing the physical basis of the process. From this position of confidence, we then can use this result to see where fingers are likely to be prominent. The size of fingers is related inversely to the characteristic grain size of a medium (Fig. 1): when the soil has a texture of silt or finer, the finger dimensions are predicted to be >1 m. Fingered flow occurs only in unstructured soils. Hence, fingered flow is expected only in soils that are predominantly sand.

Finger width is not strongly affected by the

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flux through the system (Fig. 1). Rather, the flux through the system typically affects the number of fingers that form. When the flux is increased up to the rate of the saturated conductivity of the soil, the fingers will grow in width and frequency to the point at which they finally merge to yield a flat wetting front without fingered properties. Since most sandy soils have extremely high conductivity compared to naturally occurring infiltration rates, this rarely occurs in natural conditions.

Understanding effects of prior moisture content on finger formation and finger persistence is important in managing production on sandy soils As shown by Lui et al. (1993), when soil is at field capacity, fingers will be about IO-fold wider than those developing in dry conditions. Thus, if a sandy soil is not allowed to dry completely, the bypassing effect will be reduced, if not entirely eliminated. I saw a pertinent example of the importance of this observation in Florida. Using a drip system, when irrigation was initiated before the field had significantly dried in the spring, the year's crop did well. In years when irrigation was delayed until the soil was dried, narrow fingers formed through the root zone, leaving most of the soil dry, thus damaging the crop.

Once a finger has formed in a particular location, it will remain (persist) until the soil has either dried entirely or has been completely saturated (Glass et al., 1989). Given the very high conductivity of sandy soils, eliminating persistent fingers requires either drying from the surface, which is effective to a maximum depth of about 1 m, or raising the water table. A striking example of the impact of persistence was seen in Lafayette, Ind. (Fig. 2). Distinct fingers of flow were made visible in the coarse material due to the chemical weathering of the calcareous material. Within the fingers, pebbles were readily crushed manually, while outside of the fingers the gravel strength was typical of unweathered material. Clearly these fingers had persisted for many decades.

It is crucial when initiating irrigation on dry, sandy soils that the rate of irrigation is nearly that of the saturated conductivity of the soil, so the profile starts off from an entirely wetted condition. From this initial state, any fingers will be quite large and likely not a problem from a production or contamination point of view. If problematic fingered flow is found, it can be eliminated only through complete soil drying or saturation. Given the length of time required for total drying, achieving a brief period of saturation is the most practical approach to eliminate fingered-flow pathways.

Macropore flow

Aside from very sandy soils, almost all other soils have macroscopic structure. In addition to grouping soil particles into larger units, there are structures that arise from plant and fauna activities, leaving root channels, worm holes, and animal burrows. These structural elements consist of pores that are generally several orders of magnitude larger than the characteristic grain size of the soil. For instance, in a silty soil with a median pore size of 1×10^{-5} m, the interpedface spacing would be of the order of 1×10^{-4} m, and it would have deep root channels 1×10^{-3} m in diameter. Such connected systems of large pores are referred to as macropores.

Before the 1980s, these soil features were not considered in the prediction of movement through soils. Under most natural rainfall conditions the water would go through the bulk soil, never reaching a point of saturation at which these pores would fill. However, during intense rainfall and typical irrigation conditions, the soil is taken to a state of near saturation, and these pores do fill. This results in a dramatic increase in conductivity, as the resistance to flow decreases with the square of the aperture size. Thus, such macroscopic features can dominate flow during periods of intense infiltration (a single l-mm pore will carry as much water as about 1 m^2 of uniformly packed silt textured media). Beyond the ability to allow greater infiltration, these pores allow chemicals to bypass the bulk of the soil. In this way, chemicals that would be predicted to move slowly through the soil profile can move quickly to shallow aquifers. Broadly referred to as macropore flow, this mechanism has been studied widely in the last 2 decades, and has been shown to have a major impact on the transport properties of most soils (German and Beven, 1981; Gish and Jury, 1983).

Funnel flow

Many soils are generated by deposition of material by either processes of wind, water, or volcanic activity, yielding a layered character with alternating series of finer and coarser texture due to variation in the source of the material and energy of the flow at the time of deposition. These layers have a strong effect on infiltration of water due to the capillary properties that depend on the pore size distribution in each layer. Although soils with coarser texture will typically have higher saturated conductivity, this rule breaks down in the context of unsaturated flow.

To understand this, it is useful to visualize a pair of stacked sponges, where the bottom sponge is of very poor quality with large pores, and the top sponge is of excellent quality with very fine pores. If the stack of sponges is at a slight angle and water is poured slowly onto the stack, the high-quality sponge will retain the water and let it flow over the lower-quality sponge. Similarly, in the layered soil system, the finer-textured pores will retain infiltrating water and divert the water over the coarser layer. This process, known as funnel flow, can intercept infiltration from broad areas into focused streams of infiltration (Kung, 1990). In a potato field studied in Wisconsin, water landing on an area of 2500 m^2 was focused to an area <0.25 m^2 by the time it reached the water table at a depth of 6 m (Kung, 1990). This 10,000-fold reduction of area of flow gives rise to a proportionally increased vertical transport velocity, dramatically reducing the time of travel of water and solutes from the soil surface to unconfined aquifers.

Management guidelines

As shown above, there are processes that can cause a portion of the water to leave the root zone rapidly through a small portion of the profile in soils of all textures. The key to preventing groundwater contamination is to use our understanding of these flow processes as a parameter in our irrigation management.

Traditionally the irrigation system designers' concerns were dominated by the following:

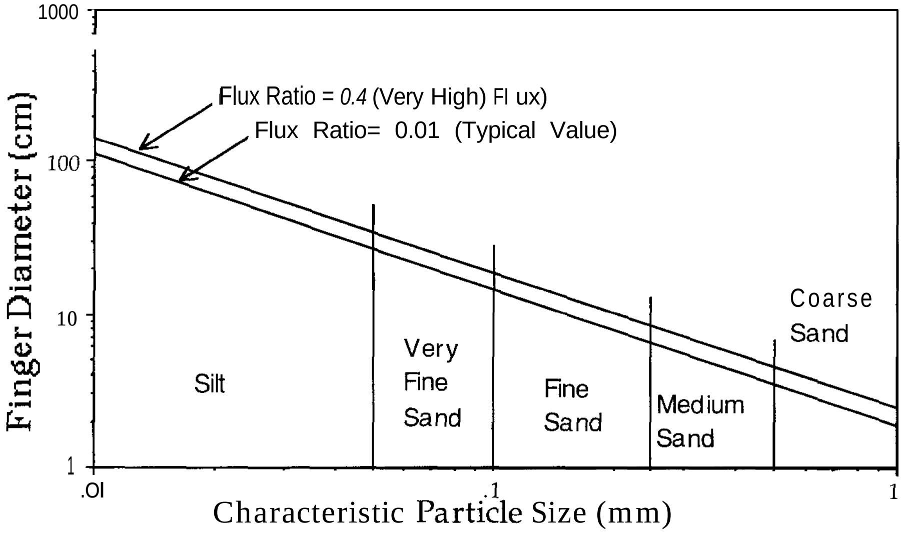

Fig. 1. *Dependence of finger width on the characteristic grain size of a soil and the relative flux (q/Ks) into the system (using the results of Parlange et al., 1990)*

1. Selecting a system that will work with the topography of the land (e.g., can't use flood irrigation on rolling hills).
2. Selecting a system that suits the crop-machinery system the farmer uses.
3. Choosing application rates that suit the infiltration capacity of the soil (in flood irrigation, this means that the application rate should be much higher than the infiltration capacity).

Irrigation efficiency was typically of paramount interest, as water is typically a scarce commodity, either due to pumping costs, or overall supply.

In the past 3 decades, preventing environmental degradation has joined the list of decisive concerns to agriculturists. Irrigation system designers have aided in environmental protection through improved irrigation uniformity: If a field is not being irrigated uniformly, and yet all points become fully irrigated, there will be regions of excess irrigation that will contribute percolation to the groundwater. This line of argument still only considers movement in the absence of preferential flow, and few have addressed the issue of how understanding preferential flow should influence irrigation operation.

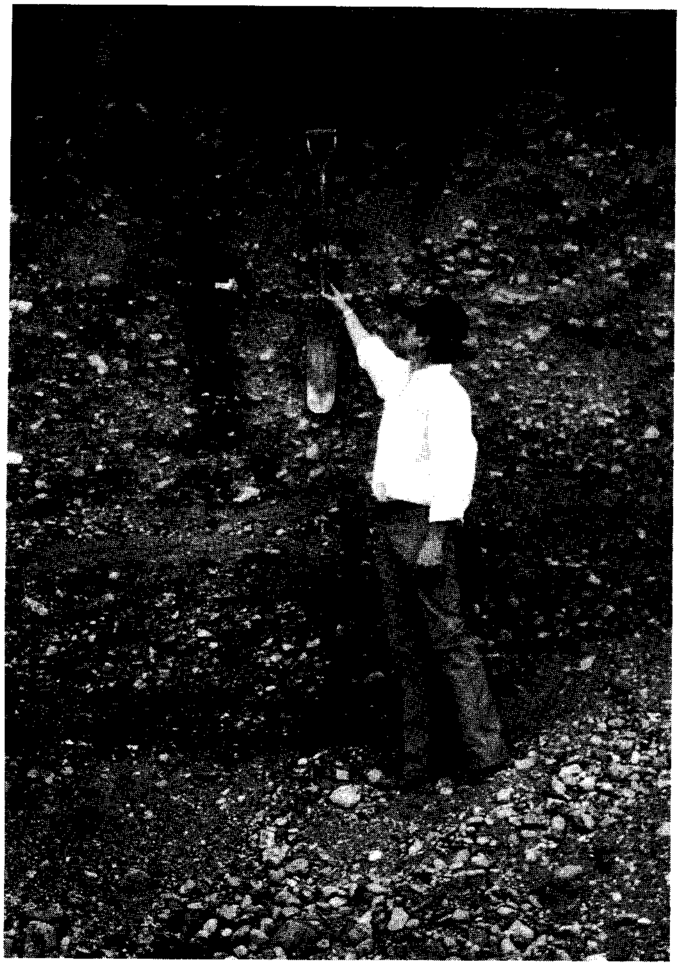

Fig. *2. R. Bryant stands next to glossic features in a soil believed to have been formed as a result of fingered flow that persisted for periods of hundreds, if not thousands, of years. The apparent difference in coloration in the fingers is not due to moisture content, but results from the extensive chemical weathering of the material within the fingers.*

To address the impact of preferential flow on irrigation, consider the case of irrigating a coarse soil. There are two forms of preferential flow that should be expected: fingered flow and funnel flow. Irrigation on coarse-textured soils typically uses overhead sprinkler or drip irrigation, as surface irrigation methods (e.g., flood and furrow irrigation) are not amenable to the high infiltration capacities of these soils. At the start of the irrigation season the first consideration must be to avoid finger formation in the root zone by ensuring that the root zone starts in a moist condition. If the soil is starting from a dry condition, a burst of irrigation at a rate close to saturated conductivity of the soil of sufficient amount to wet the root zone will erase any residual fingers and render the profile far less susceptible to new finger development. From this point, the profile should not be allowed to dry completely during the irrigation season.

Using a drip irrigation system, such a process can involve great additional expense and, therefore, be impractical. In fingered flow, water from drippers is likely to go vertically downward in a path of area equal to the saturated conductivity of the soil divided by the application rate. For instance, a 5-liter·h^{-1} (0.005 $m^3 \cdot h^{-1}$) emitter in a coarse soil with conductivity of 1 $m \cdot h^{-1}$ will keep a column of soil wet with a cross-sectional area of about 50 cm^2. If the plant roots go to a depth of 0.5 m, the irrigated volume of soil is just 2.5 liters (to determine finger size on a site, simply drip about 20 liters of dyed water onto an area of completely dry sand and measure the diameter of the wetted area through excavation). If this soil had a field capacity of about 10%, any application above 0.25 liter would be lost below the root zone. In such a case the system must be operated in bursts of 3 min at a time; long enough to refill 0.25 liter of holding capacity. The next irrigation would be required when the plant had transpired this volume. This high-frequency, low-volume approach is well adapted to drip irrigation, but, if ignored, water waste and aquifer contamination, particularly if chemigation is used, is likely.

Still considering coarse soils, what are the prescriptions to handle the possibility of funnel flow? Two management practices can be used to minimize the effects of funnel flow. The first practice is applying high rates of water. The funneling only occurs when the flow is slow enough for the fine layers to carry water laterally under unsaturated conditions, and the high rate of application lets water cross through the fine layers into the coarse. The second practice is applying water for a short duration with high frequency. Irrigating to keep the top 30 cm well wetted would be suitable for most annual crops. If a longer period of irrigation is used, the water will end up being restricted by an upper, fine layer, then funneled by a lower, fine layer. The worst prescription for sites with layered soils is slow over-irrigation.

In the case of finer, structured soils, macropore flow must be avoided. Macropore flow occurs when water is applied at rates that approach the infiltration capacity of the soil in a given horizon. In this case, the prescription is exactly opposite of that for coarse soils: apply the water as slowly as required to avoid saturating the soil. In the case of a clay soil, macropore flow was eliminated by reducing the irrigation rate to 0.0003 $m \cdot h^{-1}$ (Selker et al., 1995). These extremely low rates of irrigation may be achieved by pulsing the irrigation system or by using emitters designed to provide continuous low-rate irrigation,

Conclusions

Many aquifers have been contaminated through ignorance of the possibility of rapid flow of water through soils. Such preferential flow can be avoided by following a few simple rules that depend on the nature of the soil at the site. These rules are different from what one might expect using native intuition, and thus have long been violated by irrigation system designersand operators When understood, preferential flow can be avoided to save water and protect aquifers underlying agricultural lands.

Literature Cited

Gardner, W.R. 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85:228-232.

Gish, T.J. *and WA. Jury. 1983.* Effect of plant roots and root channels on solute transport. Trans. ASAE 26(2):440-444, 451.

German, P. and K. Beven. 7981. Water flow in soil macropores. I. An experimental approach. J. Soil Sci. Soc. 32:1-13.

G/ass, R.J, T.S. Steenhuis, and J.-Y Parlange. 1989. Mechanism for finger persistence in homogeneous, unsaturated, porous media: Theory and verification. Soil Sci. 148(1):60-70.

Green, W.H. and G.A. Ampt. 1911. Studies in soil physics, I, The flow of water and air through soils. J. Agr. Sci. 4:1-24.

Hill, DE. *andJ.-Y. Parlange. 1972* Wetting front instability in layered soils. Soil Sci. Soc. Amer. Proc. 36:697-702.

Kung, K-J.S. 1990 Preferential flow in a sandy vadose soil: I. Field observations. Geoderma 46:51-58.

Lawes, J.B., J. H. Gilbert, and R. Warrington. 1882. On the amount and composition of rain and drainagewaterscollectedat Rothamsted. William Clowes and Sons, London.

Lui, Y., B.R. Bierck, J.S. Selker, T.S. Steenhuis, andJ-Y. Parlange. 1993. High intensity x-ray and tensiometer measurements in rapidly changing preferential flow fields. Soil Sci. Soc. Amer. J. 57:1188-1192.

Parlange, J.-Y. and DE. Hill. 1976. Theoretical analysis of wetting front instability in soils. Soil Sci. 122:236-239.

Parlange, J.-Y, R. J. G/ass, and TS. Steenuis. 1990. Application of scaling to the analysis of unstableflow phenomena. Scaling in soil physics. Spec. Publ. 25, Soil Sci. Soc. Amer., Madison, Wis.

Philip, J.R. 1969. Theory of infiltration. Adv. Hydrosci. 5:215-296.

Selker, J.S., TS. Steenhuis, and Y.-J. Parlange. 7992. Fingered flow in unlayered media under uniform irrigation. Soil Sci. Soc. Amer. J. 56:1346-1350.

Selker, JS., W Cao, and R. Roseberg. 1995. Use of ultralow rate application devices to eliminate macropore flow during irrigation. Proc. 5th Intl. Microirr. Congr., 2-6 Apr. 1995, Orlando, Fla. ASAE Publ. 4-95. p, 54-59.