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**Quantifying the Process of Sodic Soil
Reclamation**

S. Miyamoto, D. Russo

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ABSTRACT

Salt and sodium (Na)-affected soils are distributed world-wide. This project was carried out (1) to develop numerical models to describe salt leaching processes in spatially variable fields, (2) to obtain the quantitative relationship between quality of percolating water and soil permeability, and (3) to evaluate chemical and physical amendments for reclaiming salt and Na-affected soils. The analysis of soil salinity data obtained from basin and leveled border irrigated orchards indicated that soil salinity variation is caused largely by soil type differences, and its distribution is spatially independent when stratified by soil type. Similar results were also obtained in furrow-irrigated fields, except that soil type differences accounted for less than 46% of soil salinity variation. Salt and Na leaching was deterred with increasing the solute-soil matrix interaction, and the deterration was greater in fine textured soils than in coarse textured soils. A descriptive model developed for water and solute transport in spatially variable fields indicated that spatial variability in salt leaching increases with increasing the solute-soil matrix interaction. A field based parametric model revealed that the quantity of leaching water required to remove salts from all parts of a basin or a leveled border increases greatly with increasing spatial variability in water intake and storage properties. The solute-soil matrix interaction is likely greater than the estimate by the double layer theory in plowed and disked fields due to soil aggregate breakdown. The reverse is likely in non-tilled soils where water may infiltrate through soil cracks. Beneficial effects of chemical amendments might appear in plowed and disked fields more so than in non-tilled soils moderately affected by Na.

SCOPE AND OBJECTIVES

Salt and sodium (Na)-affected soils are distributed world-wide. Some may have formed as a result of irrigation or mining, and others may be petrogenetic in origin. Of particular interest to US agriculture is salt and Na-affected soils recently formed in irrigated areas. These soils were originally productive, but now are salinized to the point that only salt tolerant crops can be grown. Extensive tree die-back problems recently reported in irrigated pecans of the Southwestern USA (e.g., Miyamoto and Gobran, 1983 Proc. West Pecan Conf. p. 1-12) is a typical example of recent salt-induced production problems. High salinity adversely affects the most productive segment of US agriculture.

Salt and Na-affected soils in Israel are found mostly in the Jordan Valley, the Dead Sea area and southward, and many of which can be brought into cultivation once they are reclaimed. There is, of course, a potential of secondary salinization, especially in low permeability soils irrigated with saline water or by a combination of saline water and rain runoff water. The spatially variable nature of these soils is expected to accentuate localized salt accumulation problems.

The conventional way of reclaiming saline/sodic soils typically involves prolonged ponding or sprinkling of the field so that excess salts and Na would be leached out of the rootzone. This theme is still valid especially when virgin land is to be reclaimed with a long-term return projection. Reclamation of salt-affected soils in irrigated areas, however, must be completed typically in a shorter time frame. This is particularly true when dealing with reclamation of cropped fields such as orchards and pastures. It is our view that reclamation techniques applicable to these circumstances have not been adequately developed.

The understanding of the causes and processes involved in salt accumulation may help improve reclamation techniques. In the past, high water tables were regarded as the major cause of salt accumulation. Our observation of the salted areas in the Rio Grande, however, indicate that recent salt accumulation is a direct result of inadequate soil permeability (e.g., Miyamoto et al., 1984). Similar problems also exist in other irrigated areas. Spatial variation in soil hydraulic properties seems to be compounding this problem, but this needs to be confirmed. There are also some indications that sodicity of irrigation water may be lowering permeability. This point also requires verification.

This program was then initiated with the following objectives¹:

- 1) Develop and test models for predicting leaching patterns in spatially variable fields.
- 2) Develop the quantitative relationship between quality of percolating water and percolation rates.
- 3) Evaluate chemical and physical amendments for their effectiveness in reclaiming saline/sodic spots.

¹The numerical order of the objectives is different from the original, as this order is more suited for reporting the results.

RESEARCH ACCOMPLISHMENTS

1. Leaching Processes in Spatially Variable Fields.

Our preliminary field survey indicated that high levels of salt accumulation is taking place in clayey portions of irrigated fields (e.g., Miyamoto and Gobran, 1983, Proc. West Pecan Conf. p. 1-12). This finding was followed by the examination of salt distribution patterns in a 13 ha pecan orchard established 18 years ago in the El Paso Valley, Texas. This orchard, basin-irrigated with water from the Rio Grande Project (EC_e of 1.1 dS m^{-1} and SAR of 3.2), is a typical orchard of this region in terms of soil properties, management and yields. Soil samples were taken to a depth of 60 cm at 27 m intervals along four transects at a total of 68 sites. These samples were categorized into different soil textural types, and analyzed for water content, EC, Na, Ca and Mg concentrations of the saturation extract. These laboratory data were then statistically analyzed using both conventional and geostatistics.

Results (Appendix I-1) confirmed that high levels of salt accumulation occur in areas consisting of clay or silty clay, but not of sandy loam or loam. The analysis of variance indicated that 73% of the observed salinity variation was accounted for by soil textural differences, a strong indication of textural dependence. Salinity distribution was not affected by the distance from irrigation ditches.

The results from geostatistical analysis using variograms and autocorrelation indicated that salinity distribution within a mapping unit (based on textural and profile differences) is spatially independent and at random. The frequency distribution within a soil mapping unit conformed to a normal distribution with a mean coefficient of variability of approximately 30%. This finding is somewhat contradictory to many recent reports using geostatistical

analyses. Subsequently, four additional fields were sampled, yet the conclusion remained the same.

In a subsequent study, four furrow-irrigated fields having a textural range of loam to silty clay were sampled at spacings as close as 1.5 m along 100 to 180 m furrow length (Appendix I-2). As observed in the basin or the border irrigated orchards, salinity distribution was governed by soil type distribution, but not by the distance from irrigation ditches. The frequency distribution of soil salinity classes within a mapping unit also conformed to a normal distribution. However, the variability which is accounted for by soil type differences was reduced to less than 40%, indicating that other factors also play an important role. One of them is obviously the furrow beds which not only limit the free lateral movement of surface water, but also significantly alter salt accumulation patterns.

The analysis of autocorrelation has shown that salinity distribution in one of the four tested fields is spatially dependent at a dependent distance of 46 cm. This field had a gradual change in soil texture from silty clay loam to silty clay, and the distance of the transient zone coincided with the distance of dependence. We then recomputed the distance of spatial dependence after the furrow irrigated fields were stratified by soil types. The distance of dependence was reduced to less than 15 m. Salinity distribution in Torrifluents having relatively clear and abrupt boundaries such as those found in irrigated fields of the Rio Grande Basin can be treated as a random function as long as samples are stratified by soil types and the sampling distance is not overly close (< 15 m).

Statistical analyses, either by conventional or geostatistics, help describe the pattern of salinity distribution, but do not explain why such

patterns developed. This requires a descriptive model, such as the one developed by the Co-principal Investigator at Bet Dagan (Appendixes I-3 through I-6). This model, essentially a numerical solution of transport equations for water and solutes, takes into account convection, hydrodynamic dispersion, and interactions between soil solutions and soil matrix. The interaction term consisted of changes in hydraulic conductivity, retentivity functions, anion exclusion, and cation exchange reactions associated with varying Na/Ca ratios and total electrolyte concentrations. The effect of solution composition and concentration on hydraulic conductivity was estimated from pore size distribution and swelling of clay particles using the double-layer theory.

In the first analysis (Appendix I-3), the effects of sodium adsorption ratios (SAR) and electrolyte concentrations (C) on hydraulic conductivity, soil moisture and salinity distribution were numerically analyzed for loamy sand, loam and clay loam, all of which were assumed to be homogeneous. The analysis indicates that water penetration and salt leaching can be substantially reduced due to the interaction in Na-affected soils. The analysis also indicates that the retardation caused by the interaction is likely to be greater in soils with higher clay contents. This implies that the solute composition-soil matrix interaction can accentuate spatial variability in both water penetration and salt leaching.

In the second analysis (Appendix I-4), the numerical model was extended to layered soils. Sample calculations indicate that the effect of solution composition and concentration is pronounced when fine-textured soils are overlying coarse textured soils than when coarse textured soils are overlying fine-textured soils, as the surface layer becomes the principal flow limiting layer. This is particularly true when the fine-textured soil has high SAR. When

the soil profile consists of coarse textured soils at the top and fine-textured soils at the bottom, the flow limiting layer can be the top or the bottom layer depending partly on the SAR distribution.

In the third and fourth analysis (Appendixes I-5 and I-6), the above model was extended to analyze the effect of soil solution composition and concentration on spatial variability of soil-solution interaction properties and transport of water and solutes. This system is highly complex, thus several simplifying assumptions were made. First, the system was treated as a two-dimensional process in a horizontal plane. This assumption can be justified as the horizontal plane is much larger in scale than the vertical plane in most fields of our concern. Secondly, spatial variation was treated by an assumption that a field consists of columns of soils of which properties are unique and independent of each other. This assumption can be justified at least for the soils having discrete identities such as those observed in the earlier studies in the El Paso Valley. The effects of solute composition and concentration was then evaluated by conventional statistics using mean values and the coefficient of variation (cv).

Results of the calculation (Appendix I-5) show that the solute-soil matrix interaction indeed increases spatial variability in saturated hydraulic conductivity. This effect appears most in the range of salinity and sodicity of soil solutions which causes the most rapid changes in saturated hydraulic conductivity. In the case of the Bet Dagan field, the combination was the salt concentration range of 1 to 20 meq/l when $SAR < 10$, and 10 to 20 meq/l when $SAR > 10$. The magnitude of the increase in spatial variation (evaluated by the ratio of cv to that of the inert state) was less than 1.2 when $SAR < 10$, and increased to 1.5 when SAR was as high as 20. The coefficient of variability in saturated

hydraulic conductivity in the field was estimated at 94%. Solution compositions and concentrations also had significant effects on other hydraulic parameters such as the degree of saturation, air entry values and Brook and Corey coefficients, but to a less degree than saturated hydraulic conductivity. The interaction also increased the cv of the Na retardation factor, especially at low electrolyte concentrations.

The calculation of water and salt transport considering the solute - soil interaction was carried out for the Bet Dagan field (Appendix I-6). The field was assumed to have initially a soil water content of $0.10 \text{ cm}^3 \text{ cm}^{-3}$, a SAR of 16, and salt concentration of 70 meq/l, and receives 10 cm of rain. Calculated results indicated that the interaction factor reduces a mean depth of wetting front from 41 to 37 cm and the cv from 39 to 43%. It also reduces chloride leaching front from 35 to 32 cm and the cv from 29 to 40%.

The model developed at Bet Dagan is among the most complete models currently available for describing water and solute transport in spatially variable fields, and probably one of a few in terms of including the solute-soil matrix interaction in the transport model. The accuracy of the prediction is dependent of the accuracy of input data, especially the estimate of solute effects on hydraulic conductivity. This point is discussed later in this report. This model is also capable of analyzing water and solute transport under ponding, providing that the numerical solution is carried out for the surface boundary conditions allowing nonuniform recharge rates over the field. The current boundary condition calls for a uniform and constant recharge rate at the soil surface such as rainfall or sprinklers with high application uniformity.

A field-based model was then developed at El Paso for predicting uniformity of water intake, salt leaching, crop yields, and profit function when a basin

or a border strip is assumed to consist of multiple soil types occupying discrete areas. Pounded water was assumed to infiltrate at different rates in accordance with soil type distribution, and the conventional water and salt balance computation performed at each segment as well as for the basin as a whole.

Results of the analysis indicate that spatial variability in water intake rates accentuates localized salt accumulation. If soil salinity is to be kept low throughout the basin, the quantity of irrigation required for leaching increases dramatically with increasing spatial variability. The differences in soil water retention capacities can also have a large effect on irrigation efficiency and uniformity of salt leaching.

The profit resulting from ample irrigation depends mainly on prices of water and irrigation labor relative to other production costs. The analysis has shown that in the range of water and labor prices common to the Southwestern USA, the maximum profit is achieved at an irrigation rate first reaching the potential yield. This means substantially greater irrigation requirements than ET demands, especially when saline waters are used on spatially variable fields. To reduce the irrigation water requirement, irrigation borders should be placed, if possible, along the boundary of different soil types. Another alternative is to level different elevations within a basin; lower elevation in low intake regions than in high intake regions.

2. Water Quality - Soil Permeability Relations.

As demonstrated in the previous section, the relationship between water quality (especially sodicity and salinity) and soil permeability is the crucial element in assessing water and solute transport in soils. This relationship is also important for evaluating chemical amendments used to enhance salts and Na leaching.

Laboratory studies, many of which were carried out previously at Riverside and Bet Dagan, identified several key factors which control or affect the interaction between solute and soil matrix. Those include i) clay swelling, ii) clay dispersion and pore plugging, and in more recent studies, iii) aggregate slaking. The solute-soil matrix interaction used in the transport model is based on clay swelling. The clay dispersion factor is important usually at a low salinity range (e.g., < 5 meq/liter) and is especially relevant to infiltration of rain water and the formation of surface seals. Aggregate slaking has not been studied extensively, but it can be important as reclamation usually involves deep plowing, soil drying and disking prior to leaching, which create weak soil aggregates. Leaching water probably moves through large pores between aggregates, and the break-down of the aggregates might result in reduced intake.

To evaluate the effect of aggregate slaking, three Torrifluvents (Gila silty loam, Saneli clay loam and Glendale silty clay) were collected from the Ap horizon of irrigated fields in the El Paso Valley. The clay contents of these soils were 20, 27 and 44%, respectively and consisted of mixed mineralogy (montmorillonite, vermiculite and mica). They were passed through a 2 mm screen, packed in permeameters (54 mm ID), and saturated hydraulic conductivity measured under ponding at a constant head, using 11 waters having various electrical conductivities (EC) and sodium adsorption ratios (SAR).

Results (Appendix II-1) indicate that saturated hydraulic conductivity normalized by that under sodium free and high electrolyte concentrations (HC/HC_0), decreased exponentially with increasing SAR/EC ratios in the EC range of 0.4 to 4.8 dS m⁻¹ and SAR up to 20. The relative conductivity at a SAR/EC ratio of 5 was 0.60, 0.40 and 0.18 in silt loam, clay loam and silty clay, respectively. The HC/HC_0 predicted by the Double layer theory for a clay loam soil (Appendix 1-3) at a SAR/EC ratio of 5 is from 0.18 to 0.70. The discrepancy from the projection becomes large at SAR values less than about 10 where clay swelling begins to diminish. As will be discussed later, aggregate breakdown can take place at lower SAR under low electrolyte concentrations.

In the second experiment, these soils were first leached with the saline solutions, then aggregate sizes were determined by the hydrometer method. In another set, the soils leached with the saline solutions were immersed in distilled water and the aggregate size distribution measured. Results (Appendix II-1) indicated that under high salinity and low sodicity, the peak aggregate size was 0.018 mm (average silt size and about 10 times greater than clay particles). With increasing sodicity and/or reducing salinity, the size peak shifted to smaller sizes, but not to clay sizes. This occurred even at SAR as low as 2 when electrolytes were at a low concentration ($EC < 0.5$ dS m⁻¹). After submersion to distilled water, only then increased the clay fraction. The reduction in hydraulic conductivity had a highly significant correlation with the reduction in aggregation of particles less than 0.01 mm, but not with increasing clay fractions.

In the third experiment, hydraulic gradients were measured by inserting piezometers at different depths of the soil columns. Results (Appendix II-1) revealed the largest gradient (the maximum resistance to flow) at the soil

surface in silty loam and clay loam, and a comparatively uniform gradient distribution in silty clay. The reduction in HC was probably caused by the surface seal created by aggregate breakdown at the soil surface, whereas the reduction observed in silty clay might have been caused by slaking of aggregates throughout the profile.

Since the break-down of soil aggregates occurred even at zero SAR, it was then hypothesized that Mg having a larger hydration diameter than Ca could enhance aggregate breakdown, thus reducing hydraulic conductivity. Laboratory experiments similar to the one used above were carried out in an exploratory scale. A preliminary result (Attachment IV-1) has shown that hydraulic conductivity of Ca-Na systems may be reduced by no more than 20% in silty clay and zero reduction in loam when Ca is substituted by Mg, a reduction range insignificant of any practical consequences. Thus, no further study was carried out with Mg.

A new set of experiments was performed to evaluate water intake responses to different water qualities under a condition closer to fields. The three soils were transported to lysimeters (15 m x 15 m), rotor-tilled and infiltration rings were placed (55 rings per soil type). Eleven saline solutions were applied to these infiltration rings and the rate of infiltration measured in five replicates. Results (tentative results are given in Appendix II-2) indicate that infiltration rates are largely governed by soil textural differences and compaction, but also by water quality. The extent of infiltration reduction (Fig. 4 of Appendix II-2) caused by sodicity to salinity ratio was similar to those found in the previous soil column experiments, even though infiltration measurements were taken after 4 to 5 irrigations and drying cycles.

After 11 irrigations, extending for about a year, the lysimeter was left unirrigated but received natural rainfall (about 18 cm for a period of 8 months). Thereafter, infiltration measurements were repeated for selected water compositions. We could not reproduce the infiltration data obtained earlier. The major discrepancy occurred in infiltration rate of control, which was reduced to the point that a statistical difference from other treatments became questionable. The intake rate from the control was reduced roughly to the Y intercept values when the best fit line of Fig. 4 was extrapolated. Our interpretation is that aggregates of control plots had also been destroyed due to rainfall following excessive dryness. We then placed infiltrometers in five replicates in two pecan orchards consisting of Saneli clay loam and Glendale silty clay, and irrigated five times with three of the experimental waters ($EC = 1.0 \text{ dS m}^{-1}$, $SAR = 1$, $SAR = 5$ and $SAR = 10$). We could not detect a statistically significant difference among the treatments.

It appears that the extent of the hydraulic conductivity reduction caused by low levels of sodicity and salinity is not a stable phenomenon, probably because soil aggregate itself is unstable. In addition, the presence of cracks in field soils complicates the issue. The task of predicting water quality effect on water infiltration rates in surface-irrigated clayey soils remains unfinished, and would require considerable amounts of additional research. The method developed by Co-PI at Bet Dagan is currently the best available technique, but may underestimate the effect of low SAR and EC on hydraulic conductivity near saturation in plowed and disked field soils, and likely overestimates the effect in non-tilled, clayey soils which develop cracks.

3. Chemical Amendments and Reclamation

The application of chemical amendments is a method of enhancing salt leaching and reclamation. It helps reduce sodicity and increase salinity, all of which, in theory, help increase water infiltration and percolation. There is, however, considerable uncertainty as to the effectiveness of chemical amendments (especially in marginally Na-affected soils) and the selection and application methods which produce the best results.

In the first attempt, the effect of sulfuric acid applied to irrigation water on water infiltration and associated chemical reactions was reviewed and analyzed. There has been an opinion that application of sulfuric acid to irrigation water is useless, because the acid is simply buffered by carbonate in the water, thus causing no substantial impact on water quality or water infiltration. This question was analyzed theoretically using a simple solution of carbonate equilibria both in open and closed systems. Results of the analysis (Appendix III-1) show that acid application to irrigation water at a rate not to reduce pH below 8.0 can increase Ca concentration many fold when the treated water flows into calcareous field. Whether such a practice results in increased water infiltration or not depends on the original quality of water and soil type as well as soil conditions. A guideline was presented by using infiltration data from Gila silt loam (mixed, calcareous, thermic Torrifuvent) as a function of SAR and EC. The data were obtained with lysimeters soil cropped with sorghum after 5 to 7 irrigations, and are similar to the prediction using the Double layer theory. This guideline is expected to underestimate the effect of sodicity, consequently the potential of improving infiltration by addition of chemicals in plowed and disked clayey soils, and likely to overestimate in orchard soils with limited till.

Chemical treatments of irrigation water with sulfuric acid becomes less effective as the total electrolyte concentration of irrigation water increases. This is not only because water infiltration responses become limited with increasing salinity, but because the amount of Ca released from acid application at rates to maintain pH above neutral becomes insufficient to change SAR to any substantial degree. Under this situation, as well as the situation where sodium accumulation in the soils is excessive, acid can be applied advantageously with ammonia through irrigation water. Ammonia buffers acidity of treated irrigation water, yet upon bacterial oxidation, releases acidity at the soil surface. This practice also reduces ammonia volatilization, and may prove more cost effective than using factory-made ammonium sulfate.

In the second case, sulfuric acid applied to calcareous soils affected by salts and Na was examined. In some of the earlier work, sulfuric acid and elemental sulfur were considered to have higher efficiency than neutral salts such as gypsum and calcium chloride, because carbonic acid, generated through the reaction between sulfuric acid and calcium carbonate, can also solubilize calcium carbonate. An analysis indicated that this possibility is minimal in surface-applied sulfuric acid, as carbonic acid readily escapes as CO_2 .

In the subsequent study, the effect of sulfuric acid, gypsum, calcium chloride, iron and aluminum sulfates, organic acids and a flocculant on salt and Na leaching was compared using calcareous saline soils moderately affected by Na (ESP of 13 and 17%). These soils, collected from the saline spots identified in the earlier spatial variability study, were air-dried, crushed and passed through a 2 mm screen. They were placed in columns and the amendments given above were applied in five replicates to the soil surface as well as incorporated to 30 cm at 4 to 24 mmol(+) kg^{-1} (2.5 to 15 Mg ha^{-1} in gypsum

equivalent). The soil columns were then leached with simulated Rio Grande water ($EC = 1.1 \text{ dS m}^{-1}$ and $SAR = 3.5$) under ponding.

Results (Appendix III-2) revealed that the tested inorganic compounds removed approximately equivalent amounts of exchangeable Na. However, the rate of water percolation, consequently the rate of salt leaching, from CaCl_2 treated columns became slower than other inorganic amendments after about 20 cm of water intake. Sulfuric acid and gypsum provided a lower ratio of sodicity to salinity and relatively uniform hydraulic gradients throughout the depth of soil columns. Sulfates of iron or aluminum did not provide any faster water intake. Amendment incorporation into 30 cm of the soils did not substantially alter intake rates, except in CaCl_2 treatment where water intake after application was even slower than the surface-applied case. The combined effect of rapid electrolyte leaching and the incomplete replacement of Na in the soil surface layer appeared to be responsible for the slow intake following the CaCl_2 treatment. The hydraulic gradient measured with a piezometer at different depths of the soil columns indeed indicated that high flow resistance has developed in the surface layer of less than 10 cm. This finding coincides with our earlier observation of water quality effects on soil permeability. Even at SAR as low as 6.0 and at EC of 1.1 dS m^{-1} , aggregate slaking occurred and intake rates slowed to less than 1/5 of the control. The days required to obtain water intake of 30 cm was 55 days in control, 24 days with CaCl_2 and 13 days with gypsum at a gypsum equivalent application of 7.5 tons/ha in Saneli silty clay loam, and even a greater difference was observed in Glendale silty clay. The application of organic acid and organic flocculants did not reduce SAR , and had little or no effect on the leaching process.

Based on the encouraging results from the soil column experiment, field experiments were established in the El Paso Valley at saline spots in two pecan orchards where soil samples for the above laboratory experiments were collected. Sulfuric acid, gypsum, calcium chloride and an organic acid were surface-applied in five replicates at gypsum equivalent rates of 7.5 and 15 cm/ha, and the treated fields disked. Infiltrimeters were also installed to measure water infiltration rates in five replicates. Soil samples were collected (in accordance with sampling requirements established earlier) 3, 6 and 12 months after the treatments, and analyzed for EC and SAR. Tree responses were also gauged by measuring the trunk diameter and the shoot length elongation.

In addition, a field test was carried out near Beer-Sheva by a group at Ben-Gurion University (G. Orion and Y. Demalach, 1989, ASCE Irrig. & Drain Div 115:463-473). Their experiment is totally independent of our project, but referenced here, as it complements our project. They have applied 2.8 and 5.6 Mg of H_2SO_4 per ha to a cotton field consisting of soils having ESP of 15 to 24%. They have obtained significant increases in water intake and cotton yields with the sulfuric acid treatment. Diking did not have the positive effect.

Results of our experiments at El Paso indicated no significant effects of any of the chemicals applied on salt leaching, tree trunk growth or shoot elongation. However, there were some measurable effects on reducing SAR by chemical treatments mainly through increased Ca concentration rather than reduced Na concentration in soils. Water infiltration rates were slightly higher in acid treated plots, but this positive effect diminished starting the second irrigation and thereafter.

An additional exploratory field experiment was conducted in a similar orchard on two soils; clay loam and silty clay. Three treatments were tested;

control, water run-application of ammonium polysulfide (3 times a season) and chiseling to 20 cm deep. Soil samples were collected (in accordance with the requirement established under objective 1) 18 months after the treatment, and analyzed for salinity of the saturation extract. Salinity in the clay loam plot was reduced by 30% with chiseling treatment. Chemical treatment did not reduce salinity. In the silty clay, neither treatments caused reduction in salinity. (All of these field data are still being analyzed and will be reported later as an Annex. A semi-technical article, Appendix III-3, and a general article, Appendix III-4 are attached to this report).

The field test results from Beer Sheva and El Paso are contradictory, yet are consistent with our observation on water quality effects on water infiltration rates into field soils. The message from these observations seems to be that orchard soils (non-tilled) are less sensitive to the effect of sodicity and salinity than plowed and disked fields having dry aggregates. It is possible that ponded water in orchards soils moves primarily through soil cracks. Further research is needed to understand the effect of solution composition and concentration on permeability of field soils, (especially in vertisols and entisols) before an accurate assessment of chemical amendments can be made.

POTENTIAL BENEFITS TO AGRICULTURE

This project made it possible to understand and quantify the process of salt accumulation in pecan orchards, and to offer several remedial measures to revitalize ailing trees. Tree-dieback caused by localized salt accumulation has been a serious economic blow to pecan growers and associated industries in the southwestern USA. A semi-technical article prepared (Attachment III-3) is being circulated through the extension service to alleviate this problem. The techniques evaluated should also apply to other deciduous tree crops.

The statistical analyses of salt distribution patterns performed by this project will help establish soil sampling guides for salinity and sodicity appraisal. In fact, a publication entitled "Sampling irrigated soils for salinity appraisal" was prepared for this purpose, and a copy is attached (Appendix IV-2). The understanding of the salt accumulation process also led to the development of a guide for selecting soils for orchard developments, and a copy is attached (Appendix IV-3).

The analyses of water and solute transport in spatially variable fields are directly relevant to improving water use efficiency and controlling drainage volume. The present analyses, for example, postulated several alternatives for surface irrigation management to improve uniformity of water intake and salt leaching. These measures can be implemented with minimal costs. The return to growers should come from reduced water requirements to sustain the near maximum production. Improved uniformity in water intake should also reduce excessive and unnecessary drainage from high intake regions, thus reducing the overall drainage load.

The limitation of the present study should also be recognized. For instance, this study did not address spatial variability which can exist within

what we regard as relatively homogeneous soils, such as soil cracks and preferential flow. Because of this shortcoming, we could not evaluate if basin irrigation using check borders along each different soil types will provide the efficiency of water use and salt leaching as high as that of sprinkler or trickle methods. This shortcoming also adversely affected our ability to predict the effect of water quality on increasing spatial variation in water and solute flow as well as the effect of chemical amendments in fields with no or limited till. Further research is needed in these areas of practical concern if on-farm water management practices are to be improved.

COOPERATION

This project was proposed to jointly study the problem of mutual concern; soils affected by salts and sodium. The budget and project duration were such that high levels of cooperative activities would not be feasible. Instead, each project leader has carried out several tasks which were agreed upon at the onset of this project. The cooperation and the contributions of Co-principal Investigator, Dr. Russo have made it possible to have a thorough analysis of water and solute transport processes in spatially variable fields. The review of this report should also revealed that the Principal Investigator at El Paso and Co-principal Investigator at Bet Dagan have maintained essentially an identical conceptual base to approach this task, even though each has used different techniques and tools.

This project has also identified a strong need to study water quality effects of permeability of field soils. The Volcani Institute has traditionally maintained a strong program on this area, as well. This led to a new BARD proposal. This program also generated a few spin-offs, for example, co-authoring of a chapter in Salinity Manual with R. Keren at Bet Dagan, and the use of sulfuric acid information which was generated at El Paso by a group at Beer-Sheva.

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LIST OF PUBLICATIONS

Appeared

1. Miyamoto, S. and I. Cruz. 1986. Spatial variability and soil sampling for salinity and sodicity appraisal in surface-irrigated orchards. Soil Sci. Soc. Amer. Proc. 50:1020-1026.
2. Miyamoto, S., and Cruz, I. 1987. Spatial variability of soil salinity in furrow-irrigated Torrifluvents. Soil Sci. Soc. Am. J. 51:1019-1025.
3. Russo, D. 1988. Numerical analysis of the nonsteady transport of interacting solution through unsaturated soil. I. Homogeneous systems.
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5. Miyamoto, D. 1987. Sulfuric acid effects on water infiltration and chemical properties of alkaline soils and water. Trans Am. Soc. Agr. Eng.
6. Miyamoto, S. 1989. Causes and remedies of slow water infiltration into orchard soils. Proc. West Pecan Conf.
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8. Russo, D. Field scale transport of interacting solutes through the unsaturated zone. I. Analysis of the spatial variability of the transport property. Water Resour. Res. (Submitted)
9. *ibid.* II. Analysis of the spatial variability of the field response. Water Resour. Res. (Submitted)
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11. Fukumura, K., and S. Miyamoto. Water quality effects on hydraulic conductivity and aggregate stability in selected Torrifuvents. Soil Sci. Soc. Am. Proc. (submitted).
12. Miyamoto, S. 1989. Effects of soil variation and salinity on irrigation efficiency in surface-irrigated orchards. Tech. Bull. Texas Agric. Expt. Sta. (submitted).

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13. Helmers, S. and S. Miyamoto. 1989. Effects of chemical amendments and chiseling on salt leaching in orchard soils.