MINIMIZING THE SALT BURDEN OF IRRIGATION DRAINAGE WATER IN THE PECOS VALLEY OF NEW MEXICO

George A. O'Connor, Principal Investigator

TECHNICAL COMPLETION REPORT

Project A-056-NMEX

New Mexico Water Resources Research Institute
in cooperation with the
Department of Agronomy
New Mexico State University, Las Cruces, New Mexico
March 1979

ACKNOWLEDGMENTS

Appreciation is expressed to Drs. George Abernathy and Terry Howell for their assistance in constructing the evaporation chamber; and to Dr. P. J. Wierenga for his cooperation in designing and equipping the greenhouse study. Mr. Chris Cull did much of the early work on the laboratory study as an undergraduate. His efforts are largely responsible for the success of that phase of the project. Mr. J. Glenn Davis earned his Master of Science degree by completing the laboratory phase and conducting the greenhouse study. Drs. J. D. Oster and J. D. Rhoades from the U. S. Salinity Laboratory were extremely cooperative throughout the study. Their advice and counsel are sincerely appreciated. Special appreciation is expressed to the memory of Professor John W. Clark for his steadfast support for the author in this and other projects.

The work upon which this publication is based was supported in part by funds provided through the New Mexico Water Resources Research Institute, by the state of New Mexico through state appropriations and by the United States Department of the Interior, Office of Water Research and Technology, as authorized under the Water Resources Research Act of 1964, Public Law 88-379, under project numbers A-056-NMEX and 1-4-23613.

Minimizing the Salt Burden of Irrigation Drainage Water in the Pecos Valley of New Mexico

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ABSTRACT

Pecos River water is reported to be ideally suited for minimized leaching management. Results of this research appear to substantiate that claim. Reduced leaching is shown to reduce the volume of water required for irrigation and to reduce both the volume and salt burden of drainage. These reductions were effected without detrimentally affecting soil chemical and physical properties and without reducing crop yields. Further, soil and drainage water data appear to validate the applicability of the U. S. Salinity Lab's chemical computer model to Pecos Valley conditions. Thus, the model can be used to make long term projects of actual field condition resulting from a minimized leaching program. Such projections suggest a tremendous potential for water savings by reducing leaching without serious effects on crop yields.

Keywords: Irrigation Return Flow, Precipitation, Salt Distribution, Leaching Fraction, Minimized Leaching, Salinity Tolerance

SUMMARY AND CONCLUSIONS

Minimized leaching is an irrigation management technique designed to add as little excess water for leaching as is possible without allowing salts to accumulate to levels detrimental to crop growth. Computer model predictions and greenhouse data with a Californian soil suggested tremendous potential for the technique especially with waters similar in composition to the Pecos River in New Mexico. Reported advantages of minimized leaching included reductions in water diverted for irrigation and reductions in both the volume and salt burden of drainage water, all without serious effects on crop yields. Drawbacks of the technique reportedly included increases in the SAR and EC of drainage and reductions in soil permeability due to soil dispersion and pore clogging by precipitated salts.

The purpose of this study was to evaluate the potential of the minimized leaching concept under New Mexico conditions. Specifically, the research was intended to 1) determine the applicability of the USSL computer model to New Mexico conditions, 2) to determine the effect of minimized leaching on soil and water properties and 3) to determine the effect of minimized leaching on yield of a crop common to the Pecos Valley.

Results of a laboratory column study irrigated to steady-state conditions 1) generally confirmed the applicability of the computer model to New Mexico conditions, 2) confirmed the substantial savings possible in irrigation waters diverted and drainage waters resulting from minimizing leaching, and 3) demonstrated no reductions in soil permeability or other favorable soil properties. Reducing leaching fractions in the Pecos Valley from 0.3 to 0.1 could reduce water diversions by about 0.79 acre-feet per acre per year (approx. 22% reduction) while reducing drainage by 0.77 acre-feet per acre per year (approx. 73% reduction). Salt burden of drainage would be reduced by almost 5 tons/acre/year (approx. 33% reduction). These reductions would likely occur without serious reduction in soil permeability. Even more modest reductions in leaching fractions could "save" huge quantities of water in large irrigation districts. Such "savings" could extend the life of underground water supplies and/or allow more irrigation in the area.

Results of a greenhouse study with sorghum tend to confirm other greenhouse and field studies reported in the literature. The data suggest minimal reductions in crop yields as a result of reduced leaching. Many plants respond more to the salinity of the upper portions of the root zone than to salinity at greater depths. This fact allows the increased salinity of drainage and deep soil zones (effected by minimized leaching) to occur without drastically reducing yields. Short term effects of reduced leaching on crop yields such as exhibited in our greenhouse study, and in some field studies, were not statistically significant. Long term effects have not been validated in the field, but the computer predictions suggest no drastic reductions in yield.

Reduced leaching could be instituted in the Pecos Valley of New Mexico immediately with apparent minimal risk. Careful monitoring of soil salinity would be appropriate, but severe reductions in crop yields are not expected. The savings in water needed for irrigation could reduce energy consumed in pumping, allow the growing of crops with higher consumptive uses (on the same amount of water), and possibly extend the life of irrigated agriculture in the valley for several years. Minimized leaching is not appropriate to all irrigation waters, but appears to be ideally suited for use with the Pecos River water.

Minimizing the Salt Burden of Irrigation Drainage Water in the Pecos Valley of New Mexico

The success of irrigated agriculture is dependent upon the control of soil salinity. To prevent the harmful accumulation of salts in soils, a quantity of water in excess of that required to meet the evapotranspirational needs of a crop must be passed through the root zone. This additional increment of water is called the leaching requirement (USSL, 1954). An estimate of the leaching requirement (LR) may be obtained from the salt balance concept (Schofield, 1940), and is given by equation (1).

$$LR = ECiw/ECdw \qquad (1)$$

where ECiw and ECdw refer to the electrical conductivities of irrigation and drainage waters, respectively.

Equation (1) is appropriate under steady state conditions, assuming no appreciable contribution of salts from the dissolution of soil minerals or salts, assuming no loss of soluble salts by precipitation or crop removal, and assuming uniform application of water in the field (Reeve and Fireman, 1967). The equation is widely used and is generally accepted as resulting in conservative overestimates of the leaching required. One condition in which the equation greatly overestimates the leaching requirement is when soil precipitation of salts added in the irrigation water is significant (Rhoades et al. 1973). Under these conditions, the effective ECiw is overestimated resulting in calculated LR values larger than actually necessary. Precipitation of salts from irrigation waters may be encouraged by careful water management; applying as little leaching water as possible without allowing salts to accumulate in the soil to levels detrimental to the crop. This management technique is referred to as the minimum leaching concept (Rhoades et al. 1973).

Rhoades and co-workers (1973, 1974, and 1975) have summarized the effects of minimized leaching on the composition of drainage waters resulting from the use of eight important river waters of the western United States. Minimized leaching: (1) maximizes the precipitation of calcium carbonate ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) in soil, (ii) minimizes soil mineral weathering and the dissolution of salts previously deposited in the soil, and (iii) maximizes the amount of soluble salt diverted in the water that is retained in storage in the soil profile and not returned in drainage. Reducing the leaching requirement increases the total salt concentration and sodium adsorption ratio (SAR) of drainage water, but reduces the salt burden (the total quantity of salt) by greatly reducing the volume of return flow (drainage).

Rhoades et al. (1973b) evaluated the effects of minimized leaching on the composition of waters draining from large lysimeters filled with a Californian soil and irrigated with eight important river waters of the West. The salt burden of drainage waters was shown to depend on the water composition and on the leaching fraction (LF) used. Results with synthesized water similar to the Pecos River of New Mexico were especially dramatic. The salt burden of drainage was reduced by almost 5 tons/A (11 tons/ha) per year when the LF was reduced from 0.3 to 0.1. Minimized leaching also resulted in significant savings of applied irrigation water. Decreasing the amount of extra water applied for leaching, resulted in savings of water diverted for irrigation of almost 1 acre-foot per acre (9,000 m^3/ha) per year for a consumptive use of 90 cm/yr.

Extrapolating the results of minimized leaching to an entire irrigation district (Rhoades, et al. 1973a) is even more impressive. Such data for the Wellton-Mohawk Irrigation District of Arizona are given in Table 1.

Table 1. Effect of reducing the leaching fraction (LF) on salt and water balance of the Wellton-Mohawk irrigation project (from Rhoades et al. 1973a).

	Present Conditions	With Improved Irrigation Efficiency
River Salinity	1.156 TAF	--
Acreage	65,000	--
Consumptive Use	300,000 AF	--
LF	0.42	.10
V_{iw}	517,000 AF	333,333
V_{dw}	217,000 AF	33,333
Salt Load	646,000 tons	289,000
Concentration	2170 ppm	6,375

Net Effect:

1) Gain 184,000 AF of 850 ppm river water
2) Reduce salt return by 357,000 tons
3) Reduce volume of return flow by 184,000 AF
4) Increase concentration and SAR of drain water to condition of minimal value - as would desalting plant.

The data clearly demonstrate the potential of minimized leaching to reduce the salt return to the Colorado River, to increase the availability and dilutent capacity of the river, and to reduce the volume of return flow water. Such data are particularly attractive to Pecos Valley irrigators where the chemical composition of that water allows the minimized leaching technique to effect even greater reductions in irrigation water used and in the salt burden of return flow (Rhoades, et al. 1973b).

Despite the advantages of minimized leaching enumerated above, implementation of the technique has met with considerable resistance. Most of the resistance has centered on the difficulty of controlling the low leaching fractions uniformly across a field and the expense of the high frequency irrigation systems suggested to maintain those leaching fractions. These are largely technical problems, however, that can be managed with modern irrigation techniques. Additional concerns of a more basic nature include (i) increased potential for harmful plant root-salinity interactions caused by osmotic stress when salt contents are made to increase, (ii) degradation of soil structure brought about by particle dispersion from water high in sodium (increased SAR values) and (iii) soil pore clogging as a result of salt precipitation in the soil. Limited lysimeter data from California (Rhoades et al., 1973a and Bernstein and Francois, 1973) indicated no serious reduction in alfalfa yields due to salinity buildup, but such data are relatively few in number. Similarly, literature data and calculations suggest that deterioration of soil physical properties would be minimal (Frenkel et al., 1978). Unfortunately, data for soils other than those tested at the U. S. Salinity Laboratory are scarce, and widespread acceptance of the concept is thus incomplete.

The objective of our study was to evaluate the potential of the minimized leaching concept using Pecos River water applied to an agricultural soil common to the Pecos Valley. The testing process included a laboratory study to evaluate the soil and water chemical changes that result from reduced leaching and a greenhouse study to evaluate the effects of minimized leaching on crop yields.

MATERIALS AND METHODS

Laboratory Study

The soil selected for study was the calcareous Reagan sandy clay loam, a Typic Calciorthid. Some chemical and physical properties of the soil are given in Table 2. The Reagan soil comprises about 40% of the cultivated land in the Roswell-Artesia Basin of the Pecos River Valley and is generally well suited to irrigation (SCS, 1971).

Soil was collected from Southeastern Branch Station in Artesia, N. M. Bulk samples of the soil were air dried and ground to pass a 2 mm sieve. Subsamples were then carefully packed into 9 (three per treatment) small plexiglass lysimeters, 7.0 cm ID by 25.0 cm long. Soil depth was 20 cm and all columns were packed to a bulk density of 1.3 g/cm^3 to approximate field conditions. Each lysimeter was equipped with a porous ceramic plate in the bottom of the column through which drainage was collected under a suction of 22 cm Hg. Salinity sensors were positioned about 5.0 cm from the bottom of each column to monitor soil solution salinity.

Changes in the soil solution composition resulting from irrigation management techniques are normally very slow to occur. Thus, multiple irrigations were necessary in our study to observe the effects of leaching treatment in as short a time as possible. To aid in the evaporation of water from the soil surfaces (and hence to maximize irrigation frequency), the lysimeters were placed in an evaporation chamber especially designed for the study (Fig. 1). Details of the chamber construction and performance have been reported previously (O'Connor and Cull, 1976). The chamber enclosed a slowly rotating dual turntable which supported the columns and receiver

Table 2. Some chemical and physical properties of the Reagan soil used in the study.

Parameter	Units	Value
Sand	%	45.84
Silt	%	25.02
Clay	%	29.15
Texture	--	Sandy clay loam
pH	Saturated paste	7.8
EC	mmhos/cm	2.3
SAR	$(me/l)^{1/2}$	0.84
ESP	--	1.67
CEC	me/100g soil	18.27
$CaCO_3$ equivalent	%	19.43
$CaSO_4 \cdot 2H_2O$	me/100g soil	1.13

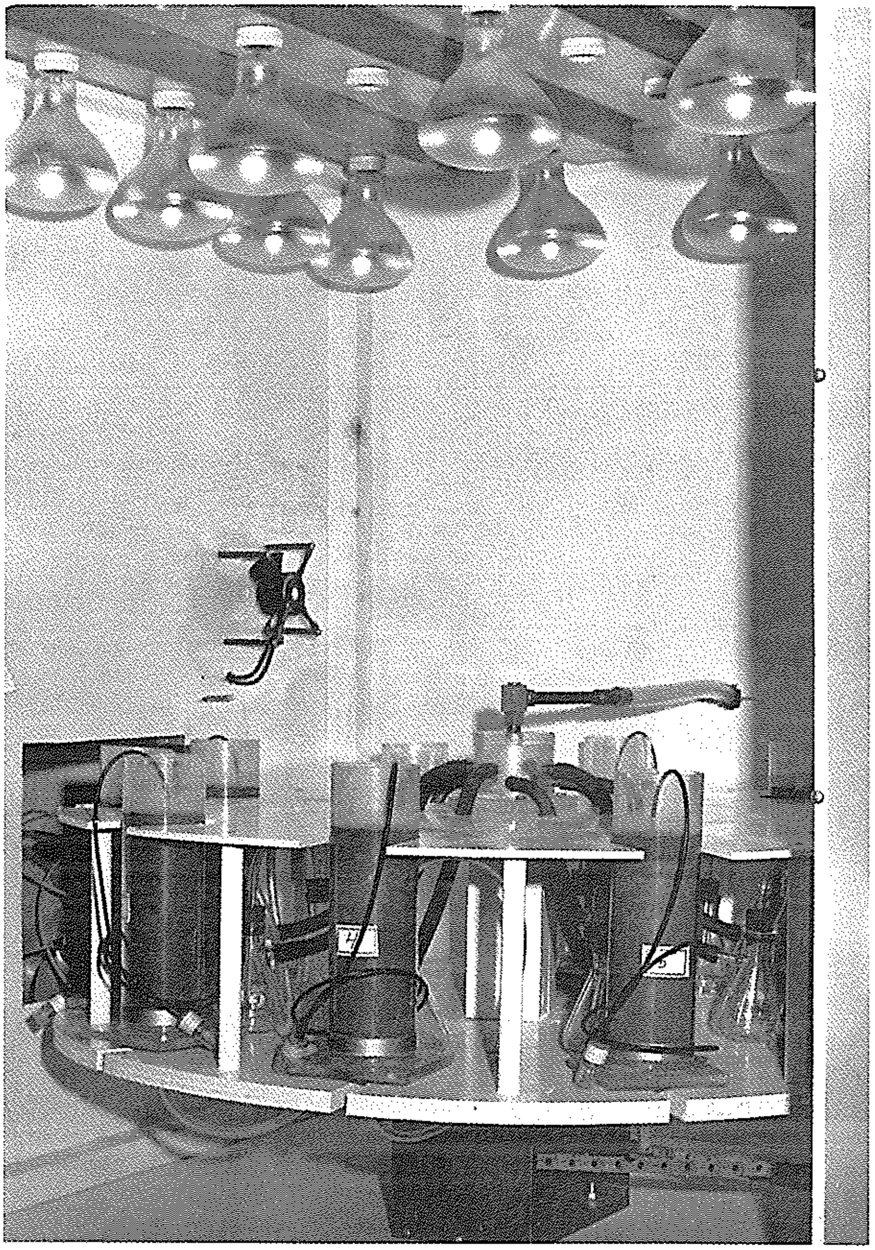

Figure 1. Evaporation chamber used in the laboratory study.

flasks. Radiant heat for evaporation was supplied by tungsten heat lamps positioned 60 cm above the soil surfaces. The lamps supplied about 2 x 10^4 luxes of light intensity at the soil surface, and heated the air temperature within the chamber during evaporation to about 50°C.

Drainage water was collected for analysis in receiver flasks positioned below the columns (Fig. 1). Suction was supplied to each lysimeter via a vacuum line which entered the rear of the unit and connected to a small plexiglass vacuum chamber positioned in the center of the turntable. A tenth plexiglass column was also positioned on the turntable to allow measurement of free-water evaporation.

The leaching treatments consisted of irrigations with a synthesized Pecos River water with the following composition all in me/1: 17 Ca, 9 Mg, 11.5 Na, 3 HCO_3, 22.5 SO_4, and 12 Cl. Water of this composition is characteristic of the Pecos River at a point south of Artesia, N. M. (USSL, 1954). A water of similar composition had been shown to maximize the effect of minimized leaching (Rhoades et al., 1974). Irrigation water was applied for calculated leaching requirements of 0.1, 0.2, and 0.4. The 0.4 treatment was considered representative of the average irrigation management currently used along the Pecos River. The 0.10 and 0.2 treatments were chosen to represent reduced (minimized) leaching rates practically attainable by farmers using normal (low frequency) irrigation technizues.

Following irrigation at the prescribed leaching fractions, the columns were covered, weighed, and allowed to stand (without suction) for 48 hours. The covered columns were then subjected to a constant suction (22 cm Hg) for an additional 40 hours and reweighed. Water lost to drainage was determined by difference in weight of columns following suction and the initial wet weight. Drained columns were uncovered and exposed to evaporation for

54 hours, or until at least 25% of the remaining soil watter was evaporated. Water lost to evaporation was determined by weight. Columns were then re-irrigated and the entire irrigation cycle repeated. The electrical conductivity of the drainage water (ECdw) was measured after each drainage cycle. Conductivity of the soil solution (ECsw), as determined by the salinity sensors, was measured at the end of each evaporation cycle. Drainage was analyzed for common anions and cations periodically.

Irrigation cycles were continued until chemical analysis of the drainage waters indicated the attainment of steady-state conditions. Each column was then sectioned into four, 5 cm segments. These subsamples were airdried, ground to pass a 2 mm sieve and analyzed for EC, pH, $CaCO_3$ equivalent, gypsum content, and water-soluble cation (SAR) status. Standard procedures (USSL, 1954) were used for all analyses.

Greenhouse Studies

The effects of minimized leaching on crop yields were determined in greenhouse studies using the same soil and water used in the laboratory study.

The first greenhouse study was begun in the summer of 1976. Soil containers 15 cm ID by 122 cm long were constructed of polyvinyl chloride. Each container had a plexiglass bottom plate equipped with a drainage hole about 2 cm in diameter. These extra long greenhouse "pots" were intended to promote normal root growth of the one plant per pot. Plants grown to maturity in normal (shallow) greenhouse pots often exhibit condensed root growth at the bottom of pots.

Reagan soil was packed to an average bulk density of 1.3 g/cm^3 in each column, as had been done in the laboratory study. Half of the columns were equipped with porous ceramic cups at 30, 60, and 90 cm to monitor the salinity of the soil solution by depth. There were thirty-five columns, ten cropped columns in each treatment, three evaporation columns with no plants, and one root observation column each in the 0.1 and 0.4 LF treatments. Observation columns were constructed of clear plexiglass to allow periodic examination of rooting patterns.

Columns were irrigated about once per week. Irrigation volumes needed were determined by weight, comparing dry weights with predetermined "pot capacity" weights. Additional water sufficient to yield LF of 0.1, 0.2, and 0.4 was added in each irrigation. Drainage was by gravity and was collected in large receiver flasks positioned below column platforms.

After 1 1/2 years, the experimental design had to be abandoned. Despite concerted efforts which included late evening irrigations, shortened irrigation intervals, and heavier irrigations, the desired leaching fractions could not be attained. Gravity drainage of the columns was so slow that drainage from one irrigation rarely bore much resemblance to the applied water volumes. Water was transmitted through the soil so slowly that plants often transpired extra (leaching) water before it appeared as drainage. Leaching fractions varied widely and inconsistently among all 35 columns. Rather than continue this frustrating and labor intensive study, a new greenhouse study was designed using smaller pots.

The new greenhouse study was begun in the spring of 1978. The smaller pots consisted of plastic waste cans 30 cm ID by 30 cm deep. Each column was equipped with 3 porous ceramic cups at the bottom to promote drainage (Fig. 2). Another ceramic cup was installed at the mid-point of the column to monitor soil solution salinity.

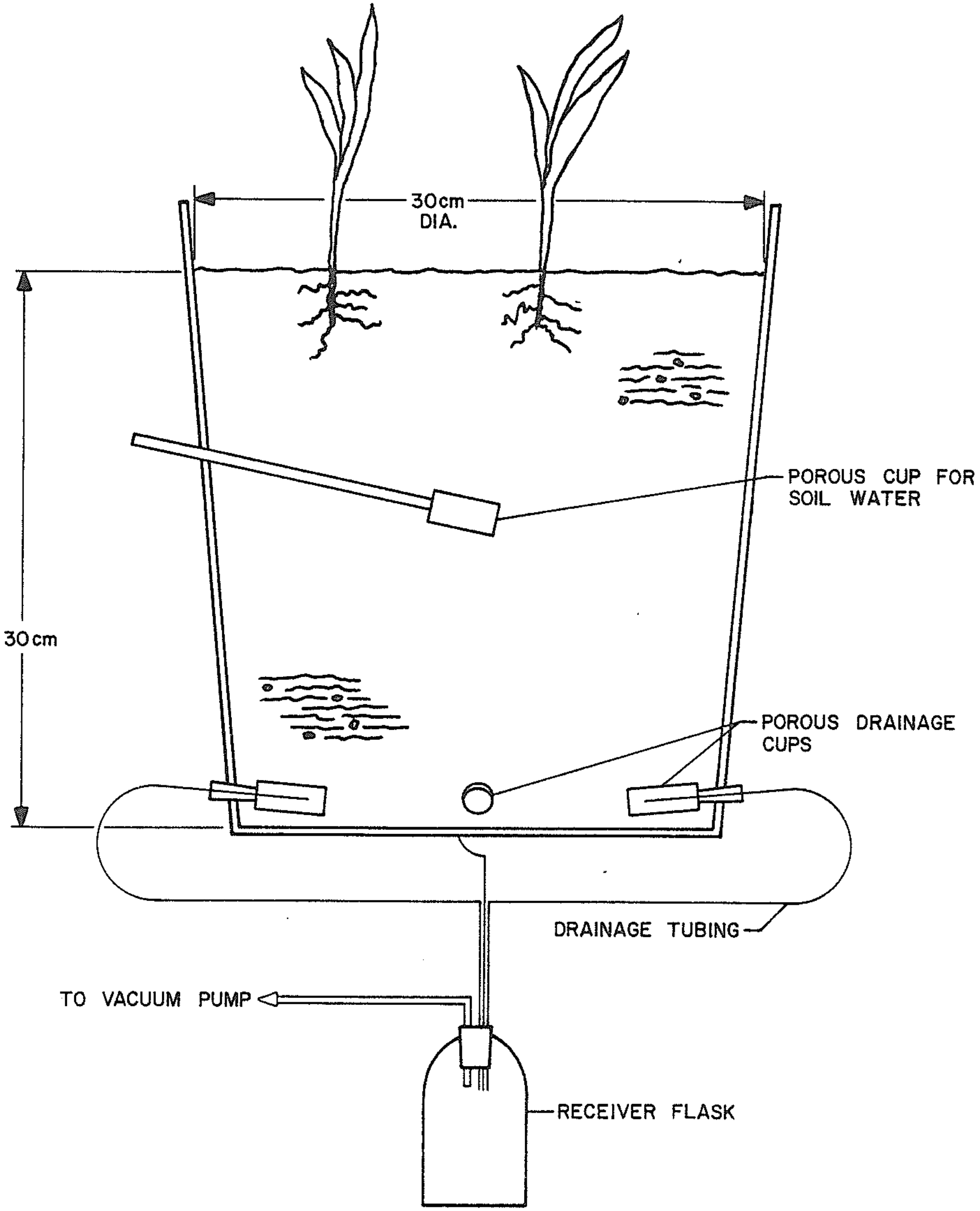

Figure 2. Diagrammatic representation of the experimental set-up used in the greenhouse study.

There were 15 columns, 5 each for the leaching treatments of 0.1, 0.2, and 0.3. The 0.4 leaching treatment was omitted since the large volumes of drainage required were deemed too difficult to obtain. Four of the columns in each treatment were cropped to sorghum, while the remaining pots were left uncropped to serve as soil water evaporation units. The pots were placed on tables with large receiver flasks positioned below each column. The flasks were connected to the drainage cups by vacuum tubing and to a vacuum system as shown in Fig. 2. The vacuum system consisted of a mechanical vacuum pump and a vacuum switch which maintained the vacuum between 18-24 cm Hg during drainage.

An irrigation cycle for these pots was similar to that used in the laboratory study. Water was applied late in the afternoon and allowed to infiltrate. Vacuum was applied and drainage collected overnight and for several hours the next morning.

Samples of the soil solution were obtained under vacuum after each irrigation. These and drainage water samples were analyzed for electrical conductivity, weekly.

Sorghum was grown as the test crop with three plants per pot. Each column was fertilized according to recommended practices which included the equivalent of 200 kg N/ha and 100 kg P_2O_5/ha. Iron was applied as the chelate, FeEDDHA, at the 5 ppm level. All fertilizers additions were calculated on a surface area basis.

Sorghum was grown until most plants had developed an exposed seed head. The plants were then harvested at ground level, dried, and weighed. The yield data were statistically analyzed using a one-way analysis of variance program developed by personnel at NMSU's Experimental Statistics Department.

Plants were irrigated every five days to a predetermined "pot capacity" plus additional water for leaching. Pots were also irrigated without crops present to assist in attainment of the intended leaching fractions. A total of 31 irrigations were applied in a 9-month period.

RESULTS AND DISCUSSION

Column Study

The column study was conducted from fall 1975 to spring 1977, during which 117 irrigation cycles were completed. Thus, the objective of maximizing irrigation frequency was met indicating that the evaporation chamber and associated procedures functioned efficiently. The high evaporative demands generated in the chamber resulted in free-water evaporation rates of 3.7 cm/day. Soil water evaporation rates averaged 0.8 cm/day, and resulted in an average 28% loss of available soil moisture (following drainage) in each drying cycle.

The success of the study was dependent on the attainment of relatively constant leaching fractions with each irrigation. Table 2 shows the desired, observed, and standard deviations of leaching fractions for each treatment over 117 irrigations. All observed LF's were slightly higher than desired, but standard deviations for each treatment were low indicating adequate control over leaching.

Table 2. Desired and observed leaching fractions obtained in the laboratory study.

LF		Standard
Desired	Observed*	Deviation
0.100	0.113	0.018
0.200	0.207	0.026
0.400	0.404	0.032

*Average of three columns

The data in Table 2 represent averages of three soil columns for each leaching treatment. Individual column values, however, were just as consistent. Thus, the experimental design and procedures were regarded as adequate to successfully evaluate the effect of LF on drainage water quality and quantity.

Two important indicators of water quality are electrical conductivity (EC) and sodium adsorption ratio (SAR). For the purpose of this study, attainment of steady-state conditions was defined as constancy of these two drainage water parameters through several irrigation cycles. Changes in EC and SAR were monitored for each column on a regular basis. The resulting data were averaged and plotted for each treatment as a function of irrigation number and pore volumes (PV) of water applied (1PV = 392 cm^3) in Figures 3-5.

Data for the 40% leaching treatment are shown in Fig. 3. Both EC and SAR reached reasonably constant values after approximately 60 irrigations, equivalent to a total of about 17 PV of applied water. There were irrigation-to-irrigation variations thereafter, but both EC and SAR reached apparent steady-state values of 7 and 5.5, respectively.

Data for the 20% leaching treatment are shown in Fig. 4. Both EC and SAR reached constant values after approximately 50 irrigations, equivalent to a total of about 10 PV of applied water. Apparent steady-state EC and SAR values were 10.5 and 9.0, respectively.

Columns irrigated at 10% leaching fraction were the slowest to approach steady-stat (Fig. 5). Approximately 90 irrigations were applied before EC and SAR reached apparent steady-state values of 15 and 13.5, respectively. Less water was applied per irrigation in the 0.1 LF treatment compared to either the 0.2 or 0.4 LF treatments. Thus, several more irrigations were necessary in the 0.1 treatment to reach the same volume of applied water. However,

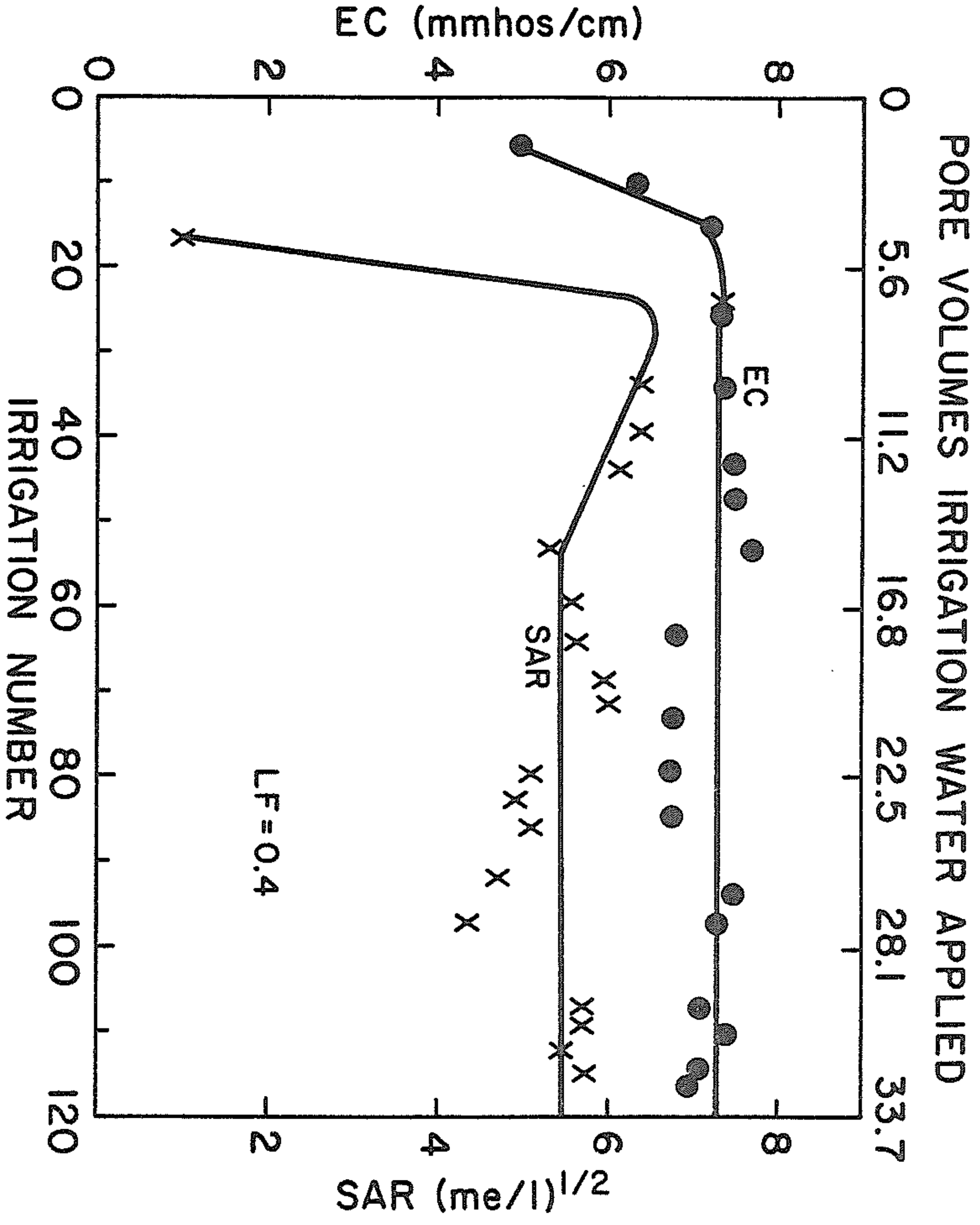

Figure 3. Drainage water EC and SAR values as a function of water applied in the 0.40 leaching treatment.

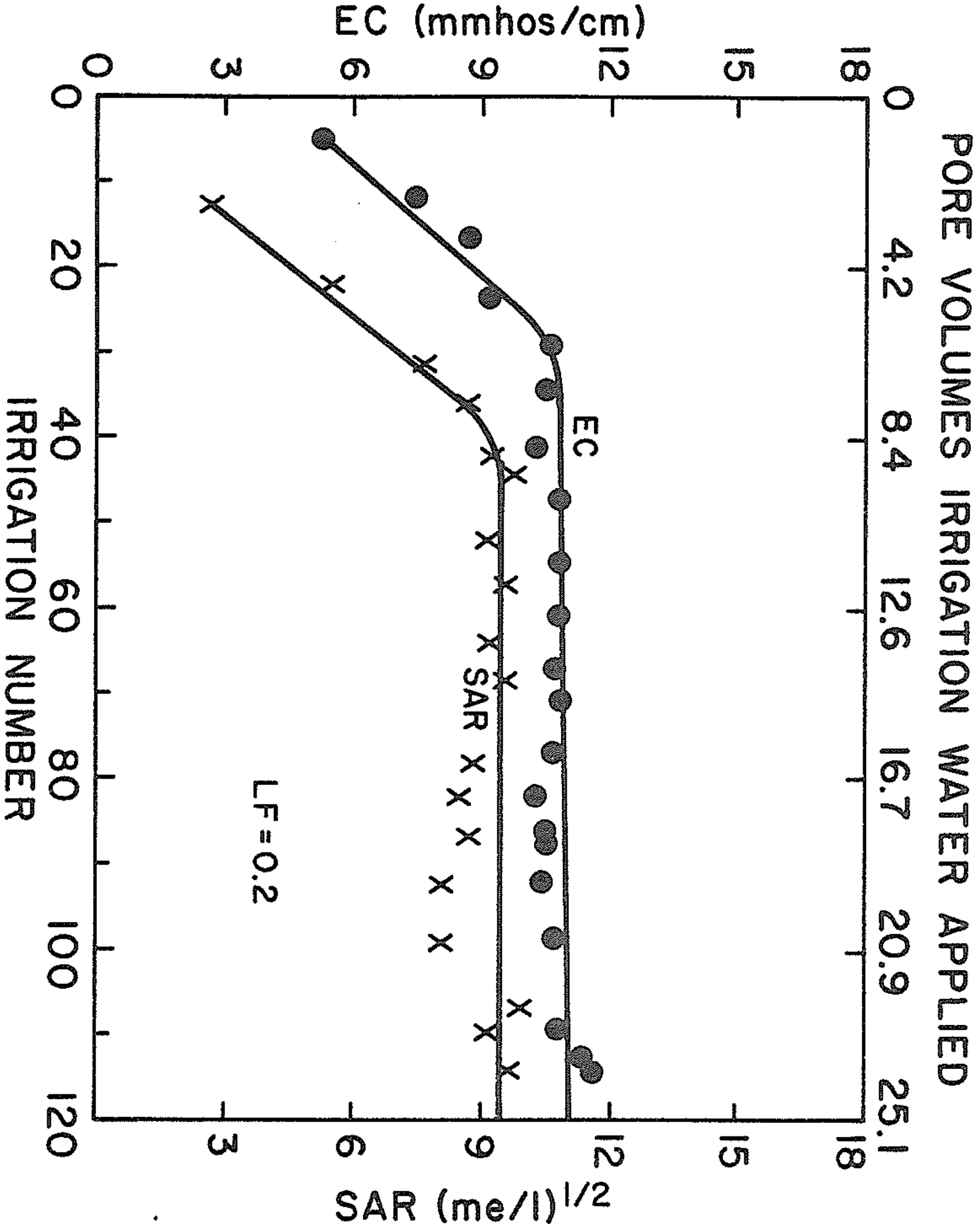

Figure 4. Drainage water EC and SAR values as a function of water applied in the 0.20 leaching treatment.

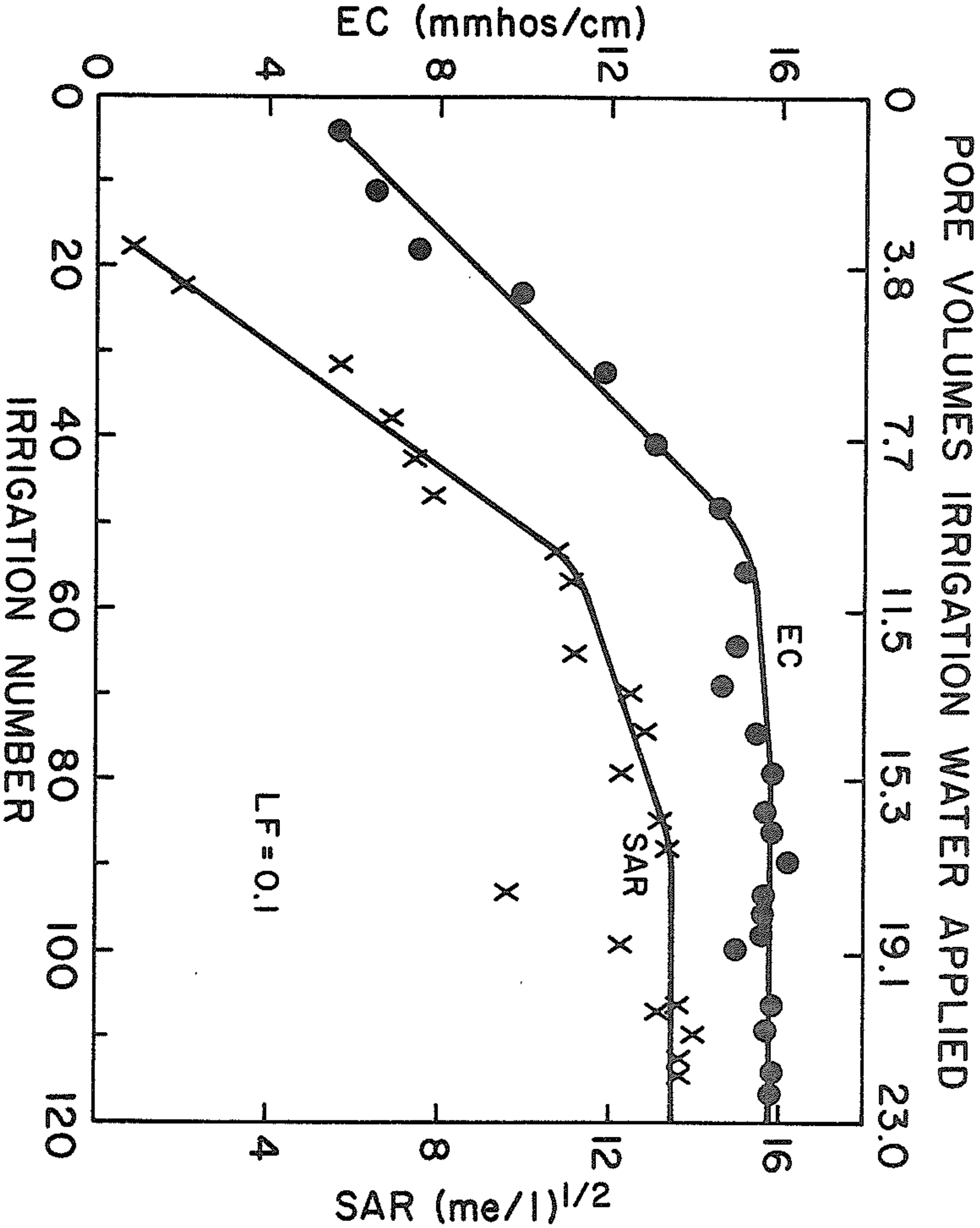

Figure 5. Drainage water EC and SAR values as a function of water applied in the 0.1 leaching treatment.

expressed in pore volumes of applied water, the 0.1 LF treatment (PV = 17) compares reasonably well with the other treatments. Steady-state conditions were apparently attained after 17 pore volumes of applied water in all treatments.

The apparent steady-state values of EC and SAR for each treatment are compared to calculated values in Table 3. Calculated values were obtained for the computer model developed by Oster and Rhoades (1975) for steady-state conditions. The model had previously been shown to accurately predict the drainage water composition of lysimeters filled with a Californian soil.

Table 3. Predicted and observed* values of EC and SAR for the leaching treatments obtained in the laboratory study.

Predicted			Observed	
EC	SAR	LF	EC	SAR
6.6	5.5	0.41	7.0	5.2
10.3	9.0	0.21	10.5	9.0
17.6	14.0	0.11	15.3	13.5

*Average of three soil columns.

Predicted values agree well with observed values in both 0.2 and 0.4 treatments. The agreement is not as good in the 0.10 treatment, but most of the discrepancy in this treatment is caused by one of the columns having much lower SAR and EC values than the other two. Thus, the average values of the parameters for all three columns in this treatment are lowered. Overall, observed and predicted values of drainage water EC and SAR agreed quite well. Additional verification of the Oster and Rhoades model is gleaned from analyses of the sectioned soil columns.

Saturation extract electrical conductivity values as a function of depth are shown in Fig. 6. Soil salinity was constant with depth for each LF treatment. The highest salinity levels were associated with the lowest leaching treatment (LF = 0.1) as would be expected, followed in decreasing order by the LF = 0.2 and LF = 0.4 treatments. The uniformity of EC with depth was apparently a result of the water utilization pattern effected by the experimental design. Water loss was by soil water evaporation in response to heat supplied by the heat lamps. Soils dried out as water was evaporated, but water loss was almost completely confined to the top few centimeters rather than from the entire soil column. Assuming that 100% of the water lost was from the top 5 cm of the column, all changes in soil solution EC would be expected to occur in this surface segment. The soil solution leaching through the remaining segments of the soil would be unchanged. Thus, the EC (Fig. 6) and SAR (Fig. 7) of the soil solutions should be relatively constant with depth as was observed in our study. The value of EC and SAR exiting from the first segment (and thus characterizing the rest of the columns) can be calculated using the Oster and Rhoades model if the water utilization pattern is known. Such predicted values are indicated on Figs. 6 and 7 and generally tend to confirm the assumed water utilization pattern of 100% consumption in the top 5 cm of soil.

The distribution of $CaCO_3$ with soil depth is given in Figure 8. The equivalent $CaCO_3$ percentage of untreated soil is indicated by the dashed line and seems to describe $CaCO_3$ distribution in the LF = 0.2 and 0.4 treatments as well. Oster and Rhoades' model predicts some $CaCO_3$ precipitation in all leaching treatments but the masses of salt involved are too small to alter the position of the line in Fig. 8 representing untreated soil. The precision of the $CaCO_3$ determination

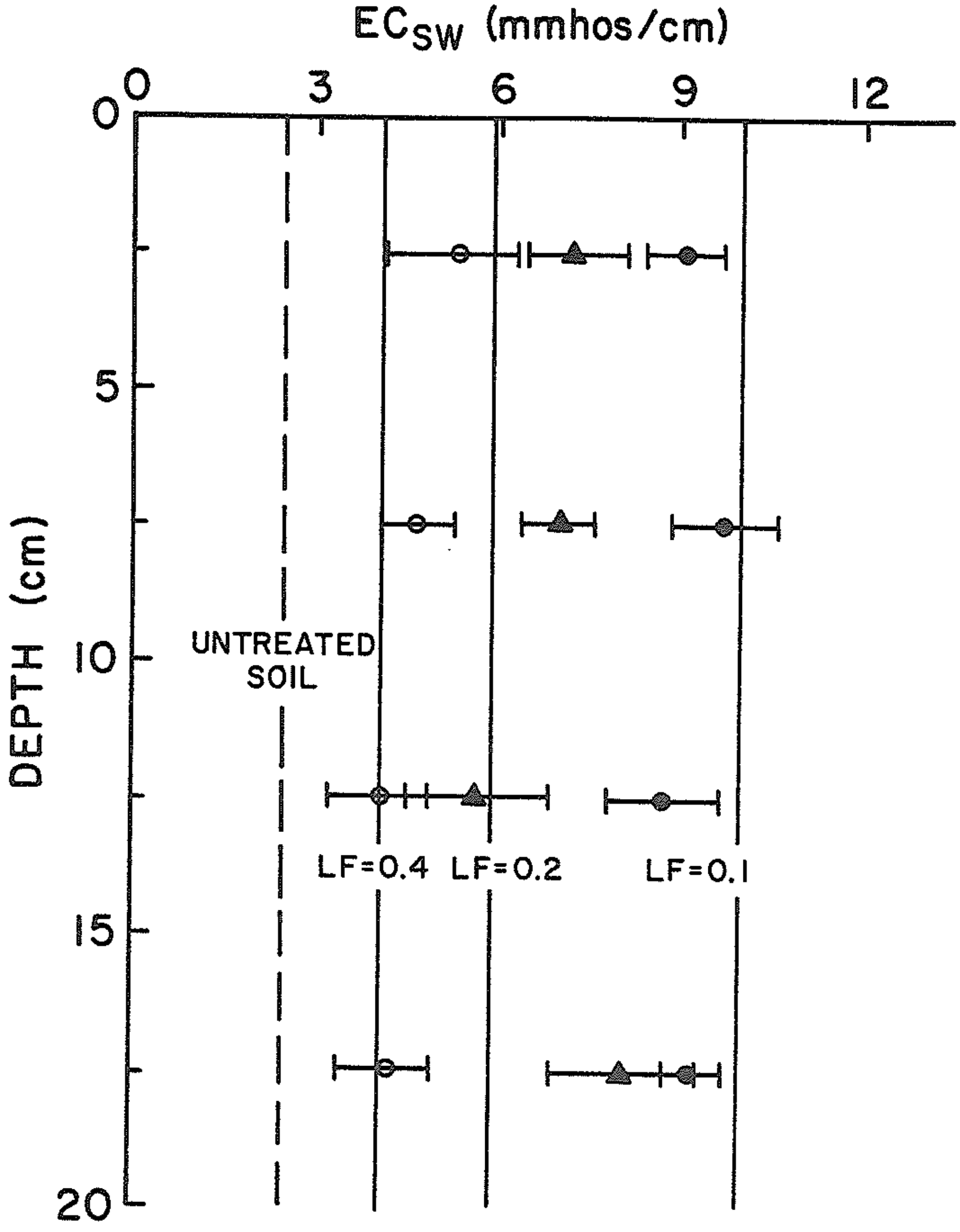

Figure 6. Average saturation extract EC values for each treatment as a function of soil depth in the lysimeters. Solid lines represent calculated values.

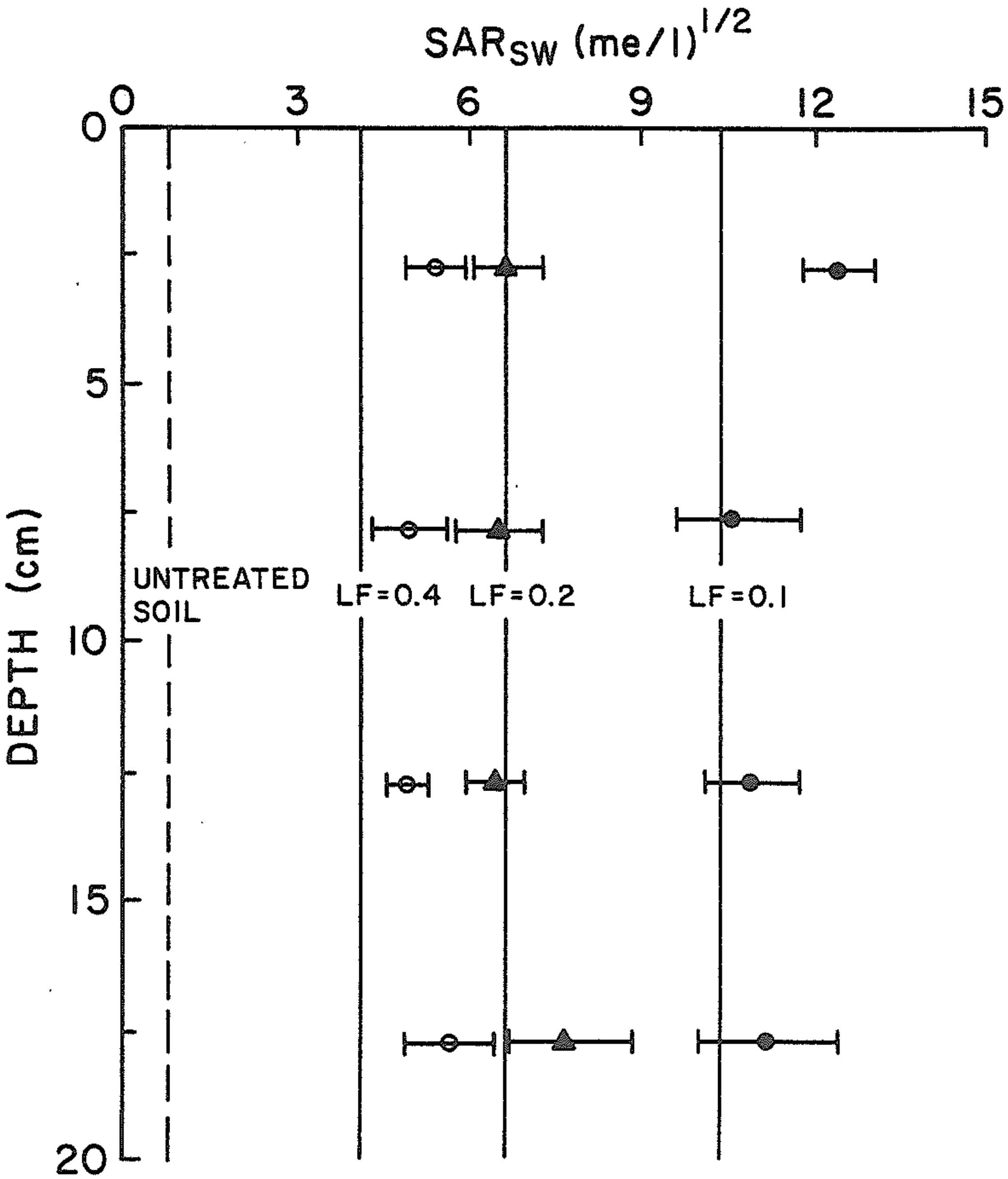

Figure 7. Average saturation extract SAR values for each treatment as a function of soil depth in the lysimeters. Solid lines represent calculated values.

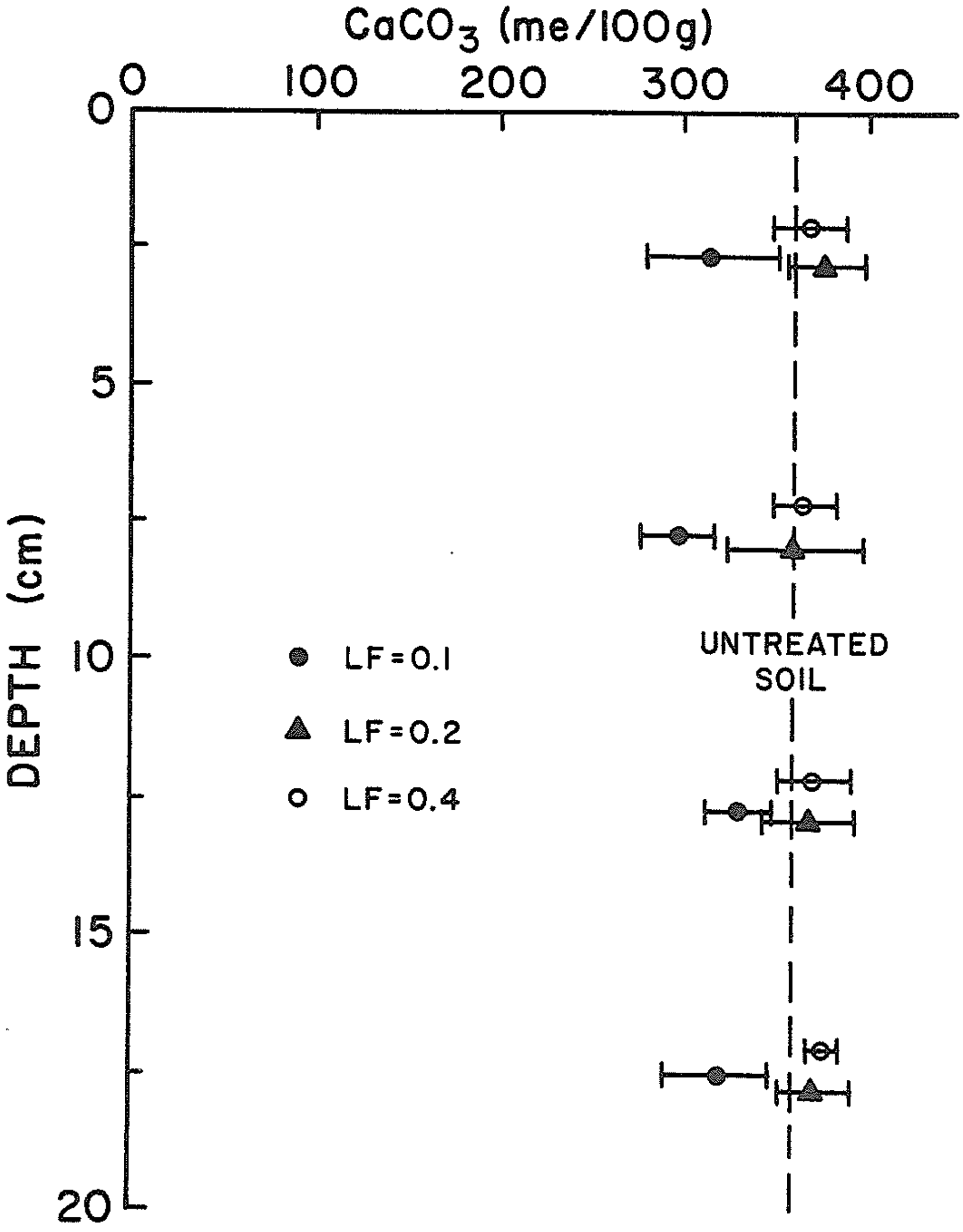

Figure 8. Average $CaCO_3$ contents for each treatment as a function of soil depth in the lysimeters.

and subsampling errors easily account for the variability indicated in the treatments. The Pecos River water is closest to saturation with respect to $CaSO_4 \cdot 2H_2O$, and gypsum is the dominant solid phase expected to precipitate as a result of minimized leaching. Only minor changes in $CaCO_3$ are expected and the data in Fig. 8 tend to confirm this expectation.

The distribution of $CaSO_4 \cdot 2H_2O$ with depth for each treatment is shown in Fig. 9. All treatments exhibit increases in soil gypsum content above that found in untreated soil. Such increases are expected if gypsum is precipitated from solution as salts are concentrated during evaporation. As inferred from data in Figs. 6 and 7, soil water evaporation occurred almost entirely from the surface 5 centimeters. Gypsum is precipitated throughout the soil column, however, during the time the entire soil approaches steady state. Solution draining from the top quarter of the column is saturated with respect to gypsum and has a SAR in excess of the native soil (Fig. 7). As this solution enters lower horizons, Na^+ exchanges with Ca^{++} on the exchange complex releasing Ca^{++} to the solution phase. As the solution phase is already saturated with respect to gypsum, this additional Ca^{++} must precipitate as gypsum. This process of exchange and precipitation continues until all segments come into exchange equilibrium at the elevated SAR values of the steady-state solution. Thus, although soil water evaporation and solution concentration is confined to the surface 5 cm, precipitation is expected throughout the column. The steady-state model of Oster and Rhoades ignores cation exchange, so that the distribution of gypsum with depth was not calculated for the leaching treatments. Jury et al., (1978 a & b) have developed a transient-state model (and experimental data verifying the model) which

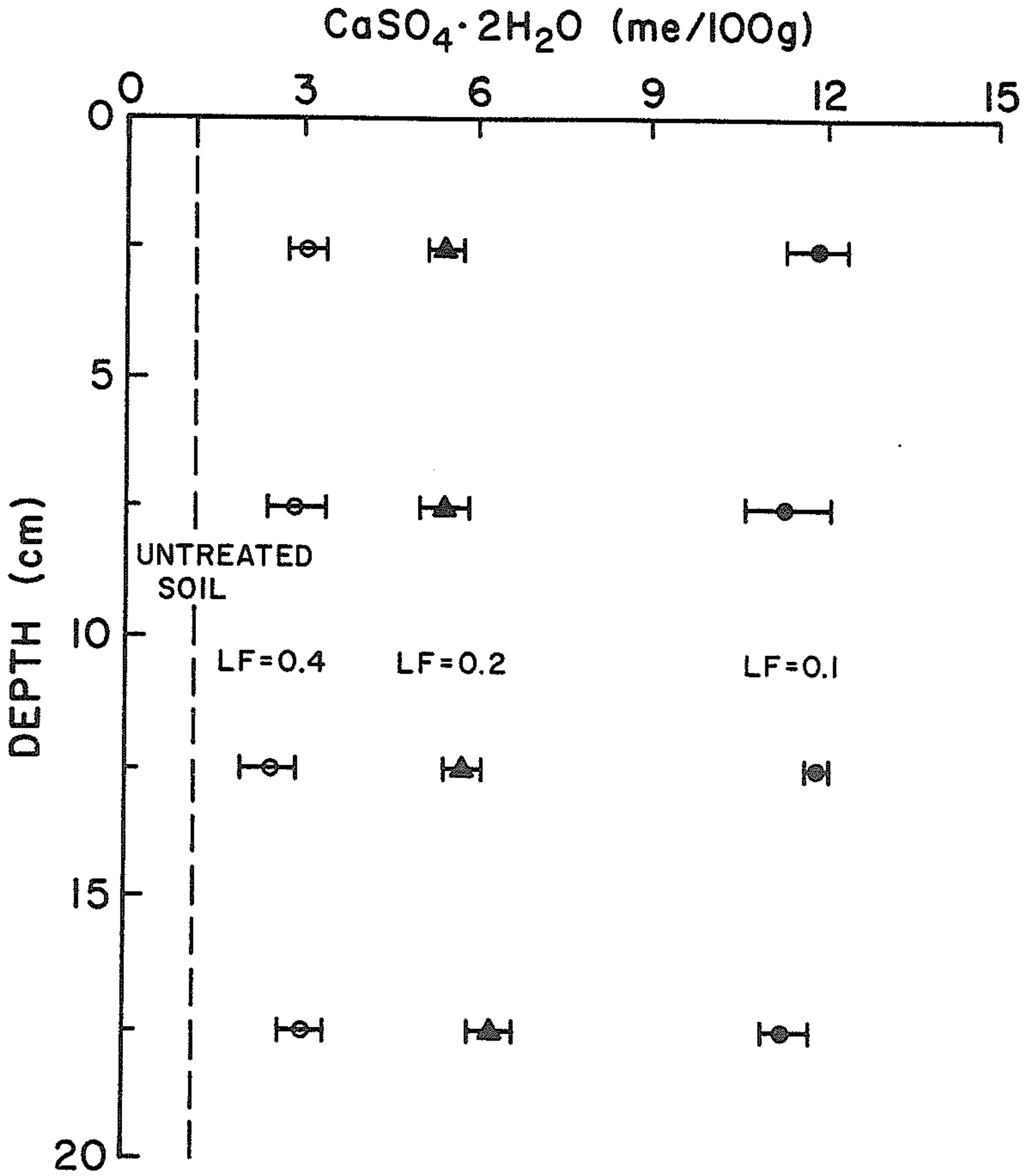

Figure 9. Average $CaSO_4 \cdot 2H_2O$ contents for each treatment as a function of soil depth in the lysimeters.

predicts as much as a 100% increase in gypsum precipitation in soils with large cation exchange capacities. Obviously, transient-state exchange phenomena must be considered for detailed predictions of solid phase content distributions. Predictions of solid phase deposits, or removals, utilizing only steady-state considerations (eg. Frenkel et al., 1978) may be in serious error in soils with appreciable exchange buffering capacity.

The data in Fig. 9 suggest that pore clogging due to solid phase precipitation may not be the problem originally feared. If gypsum is precipitated uniformly throughout a soil as it approaches steady-state, rather than in zones of maximum water depletion, the likelihood of pore clogging is reduced. Additionally, Frenkel et al. (1978) have calculated that a 10% reduction in pore space caused by localized (rather than uniform) salt precipitation would require from one to several decades even with high salinity water at low leaching fractions. Thus, pore clogging by salt precipitation would not appear to be a serious product of minimized leaching under Pecos Valley conditions.

Reductions in soil permeability due to particle dispersion from water relatively high in sodium (high SAR) is another potential drawback of minimized leaching. Since reduced leaching causes precipitation of mainly Ca^{++} salts, the SAR of the equilibrium solution is increased. At present, the effects of increasing SAR and total salt levels in the lower root zone are incompletely understood. Several investigators (Quirk and Schofield, 1955; Quirk, 1957) showed that soil permeability was maintained even at high exchangeable sodium levels provided that the electrolyte concentration was maintained above a critical or threshold level. The increase in EC with depth effected by minimized leaching is usually sufficient to compensate for the increase in SAR simultaneously effected whenever the input concentration is above the threshold level (Rhoades and

Merrill, 1976). Threshold values vary considerably from soil to soil and are difficult to predict without experimentation (McNeal and Coleman, 1966; Naghshineh-Pour et al., 1970; Thomas and Yaron, 1968). Unpublished data from our laboratory and extrapolation of McNeal and Coleman's data (1966), however, are pertinent to Pecos Valley conditions. These data suggest that the Reagan soil is relatively unaffected by SAR values as high as 50 as long as the EC of the irrigating solution is >1 mmhos/cm. Since the EC of the Pecos River water is >3 mmhos/cm, any concentration of the water to yield high SAR values (by reduced leaching) would result in EC values considerably in excess of the critical electrolyte concentration level. Qualitative verification of this suggestion was obtained by measuring the infiltration rate of irrigation waters in all three treatments over the last 50 irrigations. No reduction in infiltration rate occurred during this period, and infiltration rates for all columns were essentially the same.

Besides the effects on chemical and physical properties of soils, minimized leaching has important effects on irrigation and drainage water volumes. Table 4 shows the cumulative volumes of irrigation water applied and drainage water collected during the course of the laboratory study. Total consumptive use for the entire 117 irrigations averaged about 195 cm (∿6.5 acre-feet) for the three treatments.

Table 4. Cumulative volumes of irrigation water applied (Viw) and drainage water collected (Vdw) in the column study.

Treatment LF	Viw	Vdw	"Savings" in Volumes Diversion	Return Flow
	acre-ft.			
0.41	11.0*	4.2*	0	0
0.21	8.2	1.7	1.0	0.9
0.11	7.2	0.8	3.8	3.4

*Average of three columns

As would be expected, the greater the leaching fraction attained, the greater the volume of water applied and the greater the volume of drainage. The differences in water volumes involved in each treatment can be expressed as "savings" of water diverted and of water appearing as return flow (drainage). Thus, reducing the leaching fraction from 0.41 to 0.11 resulted in the equivalent of 3.8 acre-feet less water being applied to the columns. Return flow was reduced by the equivalent of 3.4 acre-feet. Reducing the leaching fraction from 0.41 to only 0.21 would result in savings of diverted water of 11.0-8.2 = 2.8 acre-feet and in a reduction of return flow of 4.2-1.7 = 2.5 acre-feet.

The data in Table 4 represent the volumes of water applied and drained for the entire laboratory study. Similar data can be calculated for a particular cropping condition, i.e. for a particular crop to be irrigated with a given water, etc. Data in Table 5 represent such a calculation using the latest chemical composition data for the Pecos River available and assuming a maximum irrigation allotment (including any leaching water) of 3.5 acre-feet. Such an allotment would allow the growing of a crop with a consumptive use of about 2.5 acre-feet. The former figure represents the water allotment dictated by the State Engineer for farmers in some stretches of the Pecos Valley.

Table 5. Calculated water volumes necessary for three leaching fractions assuming a maximum allotment of about 3.5 acre-feet of Pecos River water (EC_{iw} = 5.12 mmhos/cm).

			Savings in Volumes	
LF	Viw	Vdw	Diversion	Return Flow
	acre-ft.			
0.3	3.57	1.05	0	0
0.15	2.94	0.44	0.16	0.16
0.1	2.78	0.28	0.79	0.77

These data indicate that instituting a minimized leaching program where leaching was reduced from 0.3 to 0.1 would result in 0.79 acre-feet less water being diverted for irrigation per acre of irrigated land while simultaneously reducing return flow volumes by 0.77 acre-feet/acre. These savings would be experienced each season. For a large irrigation district, i.e., several thousand acres, the potential water savings are tremendous. Such savings in water diverted for irrigation could extend the life of underground water supplies or allow additional acreages to be put under irrigation. Savings in return flow volumes would mean less drainage to be managed. Similar calculations involving the concentration of salts in drainage indicate that minimized leaching (under the conditions expressed in Table 5) would result in reductions of salt burden of return flow by almost 5 tons of salt/acre/yr. Salt (primarily $CaSO_4 \cdot 2H_2O$) remains as a solid phase in the soil rather than appearing in the drainage water. Reducing the salt burden of drainage means less pollution of shallow ground waters and/or the river downstream when drainage is returned to these water bodies. If irrigation return flow is a significant source of pollution to the Pecos River, minimized leaching could decrease that pollution.

The more leaching is reduced (minimized), the more water is "saved" and the less salt appears in drainage. If available irrigation techniques do not lend themselves to accomplishing uniform, low leaching requirements of 10% or less, implementation of minimized leaching need not be dismissed as impractical. Even smaller reductions in leaching (improvements in irrigation efficienty) can have significant effects on water savings, especially with Pecos River water. Data in Table 5, for example, suggest that reducing leaching fractions from 0.3 to 0.15 (a readily attainable reduction) would "save" 3.57-2.94 = 0.63 acre-feet of water per acre per year in water diversion needs. In an irrigation district of 50,000 acres, this savings represents more than 30,000 acre-feet per year. The implications of the minimized leaching concept for the Pecos Valley area are tremendous and especially pertinent in light of their dwindling water supplies.

Our laboratory column data tend to confirm the applicability of the minimized leaching concept for Pecos Valley conditions. The data also support the general applicability of the Oster and Rhoades model in predicting the long term effects of reduced leaching on soil and water chemical properties. The next step in evaluating the potential of minimized leaching in New Mexico was to study crop performance under reduced leaching.

Greenhouse Study

A greenhouse study designed to demonstrate the effects of minimized leaching on crop yields was begun in the spring of 1978. Two sorghum crops were grown over a period of 9 months. Pots were also irrigated with no plants present during this period to hasten development of steady-state salinity profiles. Pots were irrigated every five days with synthetic Pecos River water. Irrigation volumes varied with leaching treatment but the average irrigation was equivalent to an application of approximately one acre-inch of water. The study was terminated after 31 irrigations resulting in a total application of 1.86, 2.38, and 2.93 acre-feet of water in the 0.1, 0.2, and 0.3 treatments, respectively.

Average cumulative leaching fractions for each treatment are given in Table 6. Control over the leaching fractions attained in the greenhouse study was not nearly as good as in the laboratory study (Table 2). As in

Table 6. Desired and observed leaching fractions obtained in the greenhouse study after 31 irrigations.

Cumulative LF		Standard Deviation
Desired	Obtained*	
0.100	0.134	0.067
0.200	0.168	0.037
0.300	0.302	0.051

*Average of 4 pots

the abandoned greenhouse study (p. 10), the major difficulty in attaining consistent leaching was the inability to collect excess water as drainage. Ceramic cups positioned at the bottom of the pots facilitated drainage collection, but there were large irrigation-to-irrigation fluctuations (Table 6). Drainage was transmitted slowly through the Reagan soil. Before the drainage could be collected, sorghum plants apparently transpired the extra water. Leaching fractions were lowest in summer months when plants were transpiring most rapidly. Meiri et al. (1977) reported similar reductions in drainage obtained and showed the reductions to be due to plant transpiration. They cautioned that, where possible, calculations of water application depth for leaching should be based on actual evapotranspiration of the crop rather than on soil moisture deficit. Unfortunately, actual evapotranspiration data for sorghum in the greenhouse were not available prior to our study.

Irrigating the pots when not cropped avoided the problem of leaching water transpiration, but defeated the purpose of the greenhouse study; determining the effect of particular leaching fractions on crop yield. The compromise irrigation schedule resulted in two sorghum crops being grown, plus several irrigations of uncropped pots between cropping periods.

Soil solution and drainage water salinities were monitored throughout the greenhouse study. Values of these parameters as a function of irrigation number are given in Fig. 10. In all treatments, soil salinity first increased rapidly (irrigations 1-5), then decreased rapidly (irrigations 6-15), as various soil depths became salinized. Over the last several irrigations (numbers 20-31), salinities in all treatments appeared to be slowly approaching some steady-state values. The final ECdw values for the 0.1, 0.2, and 0.3 leaching treatments were 10.4, 9.2, and 8.0 mmhos/cm, respectively. Computer predicted (steady-state) EC values at the attained leaching fractions of 0.13, 0.17, and 0.30 were 14.4, 13.2, and 8.1 mmhos/cm respectively. Thus, only the 0.3 leaching treatment approached steady-state drainage EC values. The other treatments were apparently still far removed from steady-state. Calculations of the number of additional irrigations that would be necessary to reach steady-state in each treatment suggested a minimum of 30 over a period of at least 6 months. The poor control of leaching fractions attained during the nine months already devoted to the study did not seem to justify continuing the greenhouse project. Although steady-state conditions were not obtained during the course of the study, useful information can be gleaned from crop yield data (Table 7). Such data indicate the short term effects of instituting a minimized leaching program.

Yield data for the first sorghum crop grown are presented in the second column of Table 7. During the time this crop was being grown (irrigations 5-12), salinities of both the soil solution (at 15 cm depth) and drainage were relatively high indicating salinization of the profiles (Fig. 10). Salinities in all three treatments were approximately the same

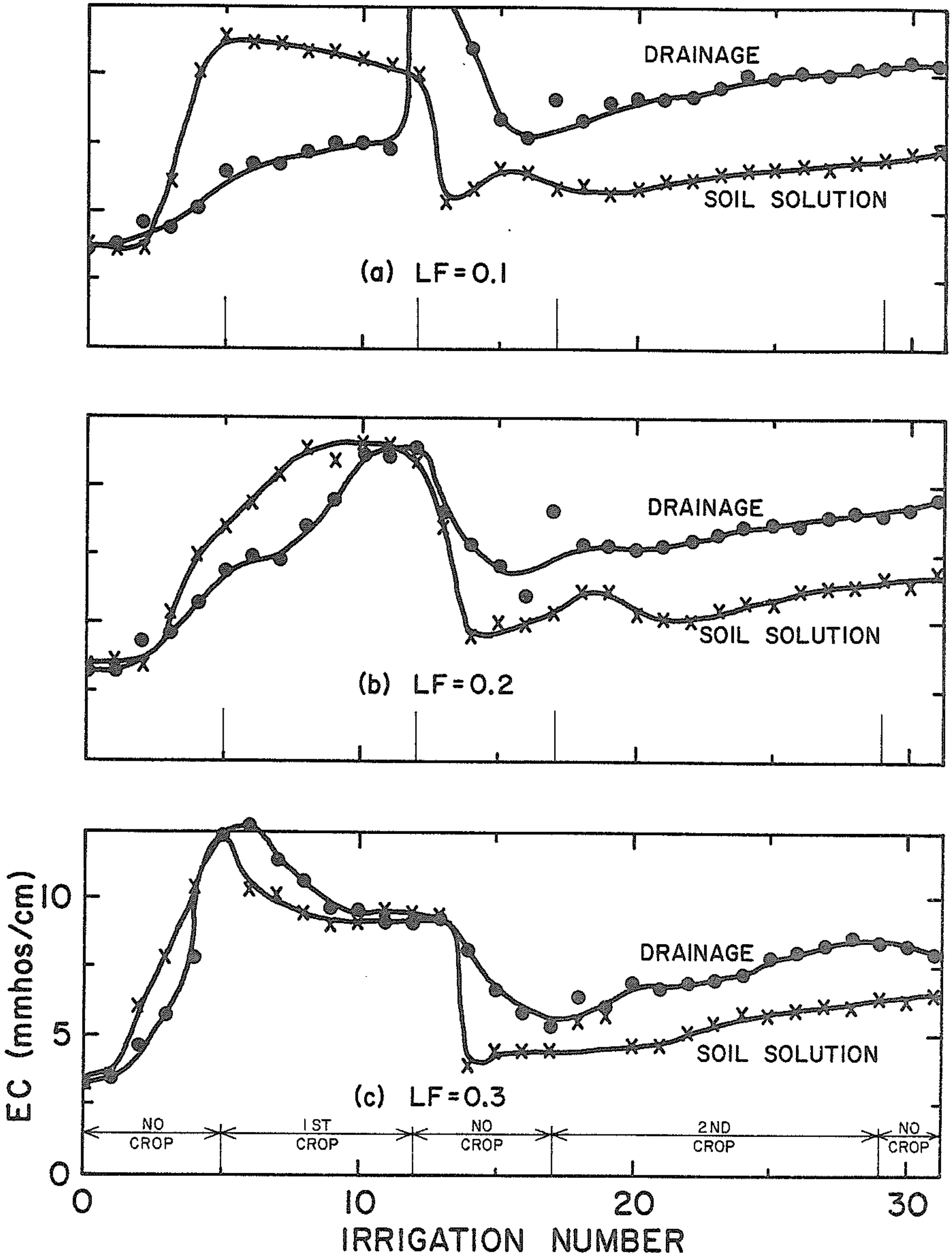

Figure 10. Average EC values of the soil solution and drainage water as a function of irrigation number for the (a) 0.10, (b) 0.20, and (c) 0.30 leaching treatments.

at the 15 cm depth, averaging about 10 mmhos/cm. Drainage water salinities were greatest for the 0.3 LF treatment and least for the 0.1 LF treatment. The standard analysis of variance of crop yields indicated no significant difference between treatments, even at the 99 percent confidence level. Apparently, sorghum plants were absorbing most of their water from the upper portion of the columns where soil salinities were approximately equal in all treatments. Thus, there was no significant effect of leaching treatment on crop yields.

Yield data for the second sorghum crop are presented in the last column of Table 7. Average soil solution EC values were very similar (5.5-6.0) during the cropping period (irrigations 17-29) in all treatments. Drainage water EC values increased steadily during the cropping period and tended to reflect leaching treatments. Average (for irrigations 17-29) drainage EC values for the 0.3, 0.2, and 0.1 leaching treatments were approximately 7.1, 8.8, and 9.3 mmhos/cm, respectively. Thus, although steady-state salt profiles were not attained, salt profiles were developed that reflected leaching treatments. Fortunately, the drainage water EC values encompass the EC value ($\sim$8 mmhos/cm) at which sorghum is reported to suffer a 50% yield decrease (EC_{50se}, U.S.S.L., 1954). From the classical leaching equation based on crop yields ($LR = ECiw/EC_{50se}$), the leaching treatments accomplished here would be expected to result in significantly different crop yields. The standard analysis of variance of crop yields, however, indicates no significant difference between treatments, even at the 99 percent confidence level.

The lack of leaching treatment (and associtated salt distribution profiles) effect on crop yield can be explained by considering a plant's

Table 7. Average dry matter yield* per leaching treatment for the two sorghum crops grown.

Leaching Treatment	Yield (g/pot)	
	First Crop	Second Crop
0.1	30.08 a	30.33 b
0.2	24.95 a	27.81 b
0.3	29.14 a	30.33 b

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*Means followed by the same letter are not significantly different at the 1% level by the New Duncan's Multiple Range Test.

normal water uptake pattern and by assuming that the dominant effect of salinity on plants is osmotic. Many plants, including sorghum, develop root systems whose density decreases with depth. Water and nutrient uptake tend to be primarily from the top 1/2 to 2/3 of rooting depth rather than uniformly at all depths. Thus, the soil solution salinity in the top 1/2 of the soil profile exerts a disproportionately larger influence on water uptake (crop yield) than soil salinity at the bottom of the root zone (drainage). Bernstein and Francois (1973) confirmed this concept by growing alfalfa at various leaching fractions. In their study, alfalfa yield was affected as much by a 1 mmho/cm difference in salinity of the irrigation water as by a ca. 20 mmho/cm difference in salinity of the drainage water. The importance of LF treatments (salt distribution profiles) will vary with crop. Crops that develop root profiles of approximately equal density throughout the soil will respond more to the average salinity of the entire soil profile. Crops that proliferate roots at shallow depths will respond more to shallow soil salinity.

If it is assumed that sorghum plants in our study tended to develop most of their roots in the top half of the pots, only minor effects of leaching treatment would be expected. In all treatments, soil salinities were approximately equal in the top half of the pots.

Bernstein and Francois' (1973) findings are the basis for suggesting that reduced leaching would have minimal effect on crop yields in most cases. Minimized leaching causes the salinity of drainage waters to increase, but the salt content of the upper zones of a soil are increased much less. Since most plants take up most of their water from the upper zones, crop yields would be expected to suffer only mildly when minimized leaching is instituted.

Bliesner et al., (1977) reported minimal effects of reduced leaching on alfalfa yields in a two year field study. Precipitation and cation exchange bufferred the salinity levels in their Utah study so well that even leaching fractions of almost zero (0.003) had no effect on yield. Several years (perhaps decades) would be necessary to reach steady-state conditions on a field basis, but even then the computer predictions of Oster and Rhoades (1975) and yield data of Bernstein and Francois (1973) suggest minimal reduction in yield in many cases.

The considerable quantities of $CaCO_3$ and/or $CaSO_4 \cdot 2H_2O$ that can be made to precipitate in soils by minimized leaching are of little concern to plants, directly. Salts must be in solution to affect the osmotic potential of the solution and hence to directly affect water uptake. Salts precipitated as solid phases in the soil thus have no direct effect on crop yields. Precipitation can affect plants indirectly by clogging soil pores or by increasing SAR and dispersing soils. Both of these processes would have the effect of reducing water and air permeability and decreasing crop yields. Our laboratory study data, however, would appear to indicate that such fears are unfounded with Pecos Valley soils and water. All of our data, in fact, tend to confirm the reported advantages of minimized leaching while suggesting that the reported drawbacks would be of minor significance.

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