CHAPTER 2C

Soil Properties and Efficient Water Use: Water Management for Salinity Control

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I. INTRODUCTION

A mixture of soluble salts is present in all soils. This mixture includes salts originally dissolved in the applied water, applied as amendments, weathered from soil minerals, or imported with subsurface water flow. If the concentration of these salts becomes excessive, crop yields will be reduced because of the decrease in osmotic potential of the soil water. To prevent harmful accumulation of salts, the soil profile must be leached periodically with an amount of water in excess of that used by evapotranspiration. Thus, where salinity is a hazard, the concept of efficient water use must be expanded to include an increment of water to meet the leaching requirement (L_r). The leaching requirement is defined as the minimum fraction of the total amount of applied water that must pass through the soil root zone to prevent a reduction in crop yield from an excess accumulation of salts (USSL Staff, 1954). Leaching occurs whenever irrigation and rainfall exceed evapotranspiration. In humid regions, rainfall is normally sufficient to periodically flush salt from the profile. In subhumid regions, additional irrigation water must frequently be applied to assure adequate leaching. Depending on the degree of salinity control required, leaching may occur continuously or intermittently at intervals of a few months to a few years.

Soils not only contain a mixture of salts, but distribution of those salts is neither uniform on an area basis or with soil depth, nor constant in time. Nonuniformity within a field is caused in large part by irrigation systems that supply water unevenly. As a consequence of this and irrigation scheduling that exceeds evapotranspiration, a large fraction of the applied water may leach through the root zone and be wasted as drainage. Present technology, including high-frequency irrigation, makes it possible to deliver water more efficiently thereby reducing excessive drainage. As we implement this technology and strive to conserve water, the minimum value to which drainage can be reduced, the leaching requirement, becomes a vital component in efficient water management.

Limitations to Efficient Water Use in Crop Production.

Two quantities establish the leaching requirement: the salt concentration of the applied water and the salt tolerance of the crop. The salt concentration of the applied water, including rainfall, is readily measured. Crop salt-tolerance, however, is more difficult to measure and has traditionally been established by measuring yields where waters of varying salt concentrations have been applied at leaching fractions approaching 0.5. Maas and Hoffman (1977) summarized salt-tolerance data for more than 60 agricultural crops. They reported salt tolerance by means of two parameters: the threshold and the rate of yield decline as salinity increases beyond this threshold. The threshold value is the maximum average salt concentration in the root zone that does not reduce yield. Where the quantity or quality of the applied water permits, efficient salinity management should not permit the average root-zone salinity to exceed the threshold value.

The leaching fraction, L, is defined as

$$L = q_D/q_I = C_I/C_D, \qquad [1]$$

where q and C represent long-term average values of the volumetric flux and the salt concentration, respectively, and the subscripts I and D refer to irrigation (including rainfall) and drainage water, respectively. Because L_r is defined as the minimum leaching fraction needed to prevent yield reduction:

$$L_r = q_D^*/q_I = C_I/C_D^*, \qquad [2]$$

where the superscript * distinguishes required from actual values (USSL Staff, 1954). The salt concentration of a relatively dilute soil solution is roughly linearly related to the electrical conductivity (σ). Because σ is easily measured, it is advantageous to express L_r as:

$$L_r \cong \sigma_I/\sigma_D^*. \qquad [3]$$

Inherent in the above equations are the assumptions that no salts precipitate, dissolve, or are removed by the crop.

Several empirical methods have been proposed to relate σ_D^* to some readily available soil salinity value. Bernstein (1964) assumed σ_D^* to be the electrical conductivity of the soil saturation extract (σ_e) at which yield in salt-tolerance experiments was reduced by 50% ($\sigma_{e_{50}}$). Later, van Schilfgaarde et al. (1974) contended that the value of σ_D^* could be increased to the σ of soil water at which roots can no longer extract water. Assuming the soil water content to be half the saturation extract water content, this value of σ is about twice σ_e extrapolated to zero yield from salt tolerance data (σ_{e_0}). Concurrently Rhoades (1974) proposed that σ_D^* could be estimated from

$$\sigma_D^* = 5\,\sigma_t - \sigma_I, \qquad [4]$$

where σ_t is taken as the salt-tolerance threshold. As will be shown later (Table 1), experimental evidence indicates that the method of Bernstein

Table 1—Comparisons of the leaching requirement (L_r) predicted by four models with experimentally determined leaching requirements for several crops.

Crop	Experimental data		Salt-tolerance data			L_r predictions				Reference
	σ_I	L_r	Threshold	$\sigma_{e_{50}}$	σ_{e_0}	$\sigma_I/\sigma_{e_{50}}$	$\sigma_I/(2\sigma_{e_0})$	$\sigma_I/(5\sigma_t-\sigma_I)$	Fig. 6	
	dS m^{-1}									
Alfalfa	2.0	0.13	2.0	8.8	15.7	0.23	0.06	0.25	0.17	Bower et al. (1969)
	4.0	0.29				0.45	0.13	0.67	0.26	
Alfalfa	1.0	0.06	2.0	8.8	15.7	0.11	0.03	0.11	0.09	Bernstein & Francois (1973)
	2.0	0.15				0.23	0.06	0.25	0.17	
Alfalfa	0.9	<0.1	2.0	8.8	15.7	0.10	0.03	0.10	0.08	Ingvalson et al. (1976)
	1.3	>0.1				0.15	0.04	0.15	0.12	
	1.6	>0.1				0.18	0.05	0.19	0.14	
	2.0	~0.2				0.23	0.06	0.25	0.17	
	3.1	>0.2				0.35	0.10	0.45	0.23	
	3.3	>0.2				0.38	0.11	0.49	0.24	
Alfalfa	1.4	<0.05	2.0	8.8	15.7	0.16	0.04	0.16	0.13	USSL Staff (1977)
Fescue, tall	2.0	0.13	3.9	13.3	22.8	0.15	0.04	0.11	0.10	Bower et al. (1970)
	4.0	0.26				0.30	0.09	0.26	0.18	
Lettuce	2.2	0.26	1.3	5.1	9.0	0.43	0.12	0.51	0.24	Hoffman et al. (1979)
Lettuce	1.4	0.25	1.3	5.1	9.0	0.27	0.08	0.27	0.18	Lonkert et al. (1976, personal communication)
Orange	1.4	<0.1	1.7	4.8	8.0	0.29	0.09	0.20	0.15	USSL Staff (1977)
Sorghum	2.2	0.08	4.0	11.0	36.0	0.20	0.03	0.12	0.10	Hoffman et al. (1979)
Sudangrass	2.0	0.14	2.8	14.4	26.1	0.14	0.04	0.19	0.13	Bower et al. (1970)
	4.0	0.24				0.28	0.08	0.40	0.22	
Tomato	2.2	>0.17	2.5	7.6	12.6	0.29	0.09	0.21	0.16	Hoffman (1980)
Wheat	2.2	0.08	6.0	13.0	20.1	0.17	0.05	0.08	0.07	Hoffman et al. (1979)
Wheat	1.4	0.07	6.0	13.0	20.1	0.11	0.03	0.05	0.04	Lonkert et al. (1976, personal communication)

(1964) overestimates, and the method of van Schilfgaarde et al. (1974) underestimates, the leaching requirement. The method of Rhoades (1974) also overestimates the leaching requirement, except at low leaching requirements.

The objectives of this discussion were to evaluate four models for predicting the mean root-zone salinity based upon experimental data, and to determine the L_r by converting the mean root-zone salinity prediction to the crop salt-tolerance threshold. The leaching requirement is presented as a function of the salt concentration of the applied water and the salt-tolerance threshold for the crop. The predicted L_r is compared with experimentally determined leaching requirements for a number of crops.

II. MATHEMATICAL ANALYSIS OF ROOT-ZONE SALINITY

Following the analysis of Gardner (1967), which was expanded by Raats (1974), the continuity equation for one-dimensional vertical flow of water through soil can be expressed as

$$\partial\theta/\partial t = -\partial q/\partial z - \lambda, \tag{5}$$

where θ is the volumetric water content of the soil, t is time, q is the volumetric flux density of water, z is the vertical coordinate that increases positively downward and has its origin at the soil surface, and λ is the rate of water uptake by plant roots per volume of soil, per unit time. For steady flow, $\partial\theta/\partial t = 0$ and Eq. [5] reduces to

$$\mathrm{d}q/\mathrm{d}z = -\lambda. \tag{6}$$

The steady-state mass balance for salt, neglecting the effects of chemical precipitation, dissolution, diffusion, and dispersion, is

$$\mathrm{d}(qC)/\mathrm{d}z = 0. \tag{7}$$

Integrating Eq. [7] and noting that at $z = 0$, the salt flux equals $q_I C_I$ leads to

$$q/q_I = C_I/C. \tag{8}$$

Evaluation of Eq. [8] at the bottom of the root zone ($q = q_D$; $C = C_D$) leads directly to the definition of the leaching fraction (Eq. [1]). This shows that the leaching fraction is based upon steady-state mass balance considerations. Expanding Eq. [7] by introducing Eq. [6] and [8] gives

$$\lambda = -q_I C_I \mathrm{d}(C^{-1})/\mathrm{d}z, \tag{9}$$

where C^{-1} is the inverse of the concentration or alternatively the dilution

Table 2—Equations for the salt concentration (C) as a function of soil depth (z), the linearly averaged root-zone salt concentration ($\overline{C}$), and the water-uptake-weighted average root-zone salt concentration ($<C>$) for three different water uptake functions (λ). The dimensionless variable x is z/Z.

Variable	Method: Exponential uptake function (Raats, 1974)	Method: Trapezoidal uptake function (W. R. Gardner, Chapter 2A)	Method: 40–30–20–10 uptake function.
Water uptake function	$\lambda_1 = \frac{T}{\delta}\exp(-z/\delta)$	$\lambda_2 = \begin{cases} 2T/Z & 0.0 \le x < 0.2 \\ 2T(4-5x)/3Z & 0.2 \le x < 0.8 \\ 0 & 0.8 \le x \le 1.0 \end{cases}$	$\lambda_3 = \frac{T}{5Z}(9-8x)$
Concentration vs. depth	$\frac{C_1}{C_I} = [L+(1-L)\exp(-z/\delta)]^{-1}$	$\frac{C_2}{C_I} = \begin{cases} [1-2(1-L)x]^{-1} & 0.0 \le x < 0.2 \\ [1-(1-L)(40x-25x^2-1)/15]^{-1} & 0.2 \le x < 0.8 \\ L^{-1} & 0.8 \le x \le 1.0 \end{cases}$	$\frac{C_3}{C_I} = [1-(1-L)(9x-4x^2)/5]^{-1}$
Linearly averaged root-zone salt concentration	$\frac{\overline{C_1}}{C_I} = \frac{1}{L} + \frac{\delta}{ZL}\ln[L+(1-L)\exp(-Z/\delta)]$	$\frac{\overline{C_2}}{C_I} = \frac{1}{5L} - \frac{1}{2-2L}\ln[0.6-0.4L] + \frac{\tan^{-1}[3(1-L)/5L]^{1/2}}{[5L(1-L)/3]^{1/2}}$	$\frac{\overline{C_3}}{C_I} = \frac{10\alpha}{1-L}[\tan^{-1}(9\alpha) - \tan^{-1}(\alpha)]$; $\alpha = \left(\frac{1-L}{81L-1}\right)^{1/2}$ $(81L>1)$
Uptake-weighted average root-zone salt Concentration	$\frac{<C_1>}{C_I} = \frac{\ln(L)}{L-1}$	$\frac{<C_2>}{C_I} = \frac{\ln(L)}{L-1}$	$\frac{<C_3>}{C_I} = \frac{\ln(L)}{L-1}$

(Raats, 1974). Equation [9] shows that the rate of water uptake may be calculated as the product of $q_I C_I$ and the negative of the slope of the dilution profile, $d(C^{-1})/dz$. Integration of Eq. [9] between $z = 0$ and any arbitrary depth z within the soil root zone gives the cumulative water uptake (w) between the soil surface and z and can be expressed as

$$w(z) = \int_0^z \lambda \, dz = q_I(1 - C_I/C). \quad [10]$$

At the bottom of the root zone ($z = Z$), w becomes equal to the transpiration rate (T), and C equals C_D. Equation [10] then reduces to

$$T = q_I(1 - L). \quad [11]$$

The water uptake function can be calculated from a measured steady-state salt profile using Eq. [9]. Alternatively, the steady-state salt distribution can be calculated from Eq. [10], provided the water uptake function (λ) is known. Table 2 gives three models for λ. The exponential uptake function (λ_1 in Table 2) was first proposed by Raats (1974). The parameter δ in this equation is an empirical constant. The trapezoidal uptake function (λ_2 in Table 2) is identical to the normalized uptake function described by W. R. Gardner (Chapter 2A). The third uptake function (λ_3) assumes that water uptake from successively deeper quarter-fractions of the root zone is proportioned as 40, 30, 20, and 10% of the transpiration rate. This uptake pattern is reminiscent of the old "40–30–20–10" rule used by Rhoades and Merrill (1976), among others. The three water uptake functions are plotted in Fig. 1. For the exponential uptake function, the parameter δ was set to 0.2 Z. In contrast to the trapezoidal and "40–30–20–10" uptake functions, the area under the exponential function is not exactly equal to 1.0, but to 0.993. This deviation from 1.0 is a consequence of the exponential nature of this uptake equation, and is considered insignificant.

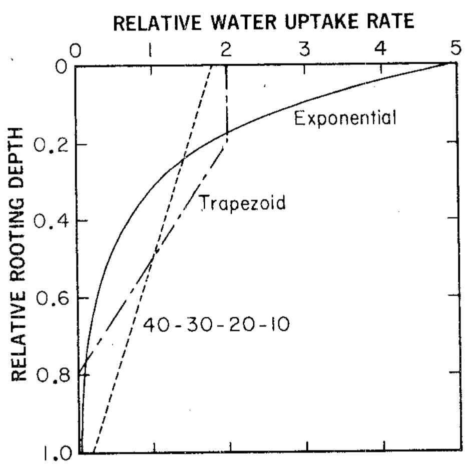

Fig. 1—Water uptake patterns as predicted by the three models presented in Table 2, relative to an uptake rate uniform throughout the rooting depth.

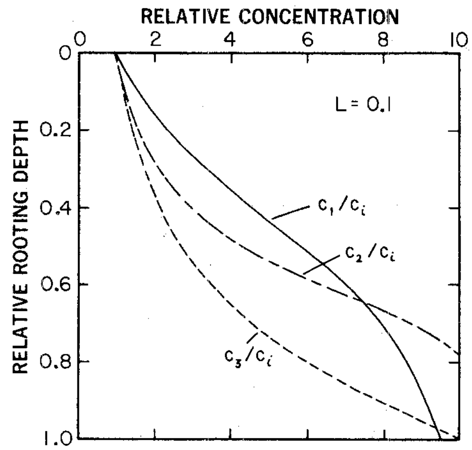

Fig. 2—Soil salinity profiles throughout the root zone at a leaching fraction (L) of 0.1; C_I, C_1, C_2, and C_3 are the salt concentrations in the irrigation water and those predicted using the exponential, trapezoidal, and 40-30-20-10 water uptake models, respectively.

Substitution of the three uptake functions of Table 2 into Eq. [10], solving the indicated integral, and using Eq. [11] results in the salt-concentration distribution equations given in Table 2. A graphical illustration of these distributions for $L = 0.1$ is given in Fig. 2. The shapes of these curves are similar to measured salt distributions (e.g., Bower et al., 1969, 1970).

There are at least two possible approaches for calculating the average salt concentration in the root zone. The linearly averaged salt concentration $\overline{C}$, can be calculated as

$$\overline{C} = \frac{1}{Z} \int_0^Z C\, dz, \qquad [12]$$

where Z is the depth of the root zone. Application of Eq. [12] to the equations for the salt concentration as a function of depth in Table 2 leads to expressions of $\overline{C}$ as a function of L for each of the uptake functions (see Table 2). Likewise, one can calculate the average root-zone salt concentration by means of a water-uptake weighted function ($<C>$),

$$<C> = \int_0^\infty \lambda C\, dz \Big/ \int_0^\infty \lambda\, dz, \qquad [13]$$

where the upper integration limit has been extended to infinity to accommodate the exponential uptake function (λ_2 and λ_3 vanish below the root zone). Substitution of the expressions for λ and C in Table 2 into Eq. [13] results in the water-uptake-weighted average root-zone salt concentrations as given in Table 2. Note that the resulting expression for $<C>$ is the same for all three water uptake functions. Bernstein and Francois (1973) showed earlier that $<C>$ is independent of the assumed water uptake distribution.

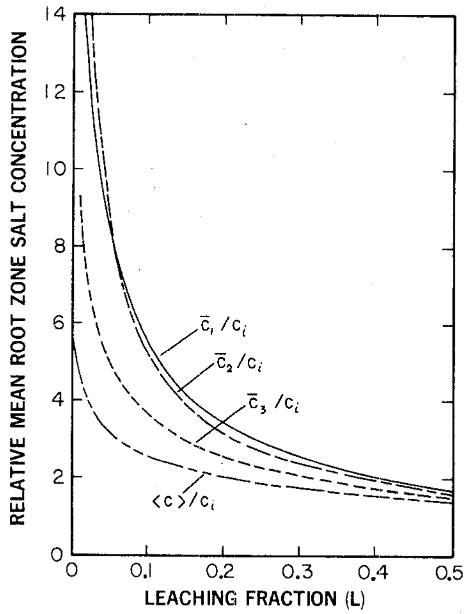

Fig. 3—Relative mean root-zone salt concentrations as a function of leaching fraction (L); $\overline{C_1}$, $\overline{C_2}$, and $\overline{C_3}$ are for the exponential, trapezoidal, and 40-30-20-10 water uptake models, respectively, of Table 2, and $<C>$ is the uptake-weighted average salt concentration for each of the three uptake models.

For comparison, the relationships between the relative mean root-zone salt concentrations and L for all four models are given in Fig. 3. The parameter δ for the exponential uptake function was taken as $0.2Z$; the reason for this choice will be obvious in the following section. Of interest in Fig. 3 is the lack of sensitivity of $<C>/C_I$ to L as compared with the other models.

III. MEAN ROOT-ZONE SALINITY

To estimate the leaching requirement based on the prediction of the average root-zone salinity, it is first necessary to verify the accuracy of the models for predicting leaching fraction. For that purpose, we took soil salinity data from the experiments of Bower et al. (1969, 1970), Bernstein and Francois (1973), Bernstein et al. (1975), Ingvalson et al. (1976), and Hoffman et al. (1979). In most, but not all, of these experiments chloride irrigation waters were used so that precipitation at low leaching fractions should not cause an error. For waters high in sulfate or carbonate, precipitation could be significant at low leaching fractions and the computer model proposed by Rhoades and Merrill (1976) may be more accurate.

For vertification of the linearly averaged expressions, the mean root-zone salinity value was calculated as the linear average of the experimentally determined salt concentration values. Each mean salinity value was sub-

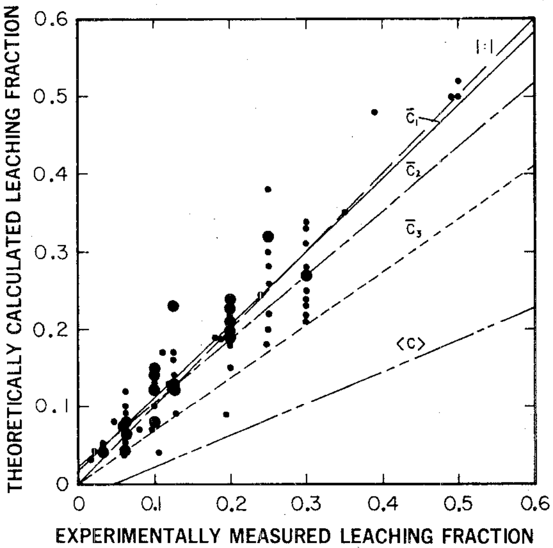

Fig. 4—Comparison of experimentally measured leaching fractions from seven experiments with theoretically calculated leaching fractions from $\overline{C}_1$, where $\delta = 0.2Z$. Also shown are the linear regressions for $\overline{C}_2$, $\overline{C}_3$, and $<C>$ for comparison. Data points are for $\overline{C}_1$ only. Larger data points indicate more than one observation.

stituted into each of the linear-average models and the equations were solved graphically for the "theoretical" leaching fraction. For vertification of the uptake-weighted expression, the experimental salt concentration values were weighted using the 40–30–20–10 water uptake function. This procedure is valid because, as shown earlier, the uptake-weighted average salt concentration is independent of the particular uptake function. The "theoretical" leaching fraction was then calculated by inserting the resultant $<C>$ value into the uptake-weighted expression. Figure 4 compares these theoretical L-values with the experimentally measured values. With the selection of $\delta = 0.2Z$, $\overline{C}_1$ best predicts the mean root-zone salinity. The other expressions all substantially underestimate L. The lines in Fig. 4 are statistically fit linear regressions through the data for each model, although only the data for $\overline{C}_1$ are shown. The correlation coefficient of the linear regression for $\overline{C}_1$ is 0.94.

The relatively good agreement of $\overline{C}_1$ and $\overline{C}_2$ with the experimental data lends credibility to their application. A disadvantage of $\overline{C}_1$, as compared with $\overline{C}_2$, is that a value must be assigned to the empirical parameter δ. However, we propose the use of $\overline{C}_1$ because of its better correlation with the experimental data.

The mean root-zone salinity, based on $\overline{C}_1$, is shown in Fig. 5 as a function of the salinity of the applied water and the leaching fraction. Note that the salinity is expressed in terms of the electrical conductivity of the soil saturation extract (σ_e) assuming $\sigma = 2\sigma_e$. Thus, the curve for $L = 1.0$ in Fig. 5 does not fall on the 1:1 line. As an example, if soil samples revealed that the mean soil salinity was 5 dS m^{-1} and the salinity of the applied water

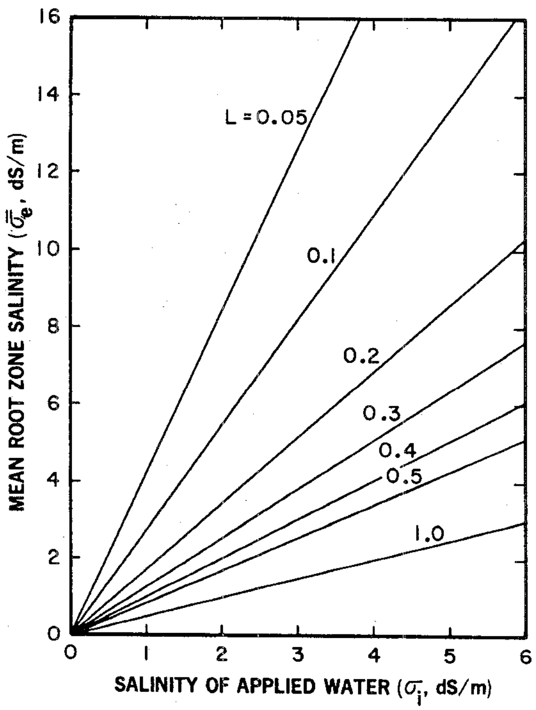

Fig. 5—The mean root-zone soil salinity as a function of the salinity of the applied water and leaching fraction (L). Curves are based upon the linearly averaged root-zone salt concentration for the exponential water uptake function ($\overline{C}_1/C_I$ in Table 2).

(σ_I) was 3 dS m^{-1}, the leaching fraction would be estimated to be 0.21 under steady-state conditions.

The large differences between experiment and theory for $\overline{C}_1$ and $\overline{C}_3$ indicate that, at least under saline conditions, the 40-30-20-10 rule of thumb often quoted as the distribution of water uptake through the root zone underestimates the water lost from the upper portion of the root zone. The water uptake distribution is approximately 71-21-6-1 based on $\overline{C}_1$, and 50-35-14-1 based on $\overline{C}_2$. Although evaporation was ignored in the theoretical development, it may account in large part for the high proportion of water lost near the soil surface.

IV. LEACHING REQUIREMENT PREDICTION

From the definition of leaching requirement as stated in Eq. [3], the unknown term in predicting L_r is σ_D^*. Unfortunately, this definition is not suited for use of the large number of experiments designed to establish the salt tolerance of agricultural crops. A more convenient quantity for evaluating leaching requirement is the crop salinity threshold value. If mean soil salinity is replaced by the threshold, the result is a graph similar to Fig. 5,

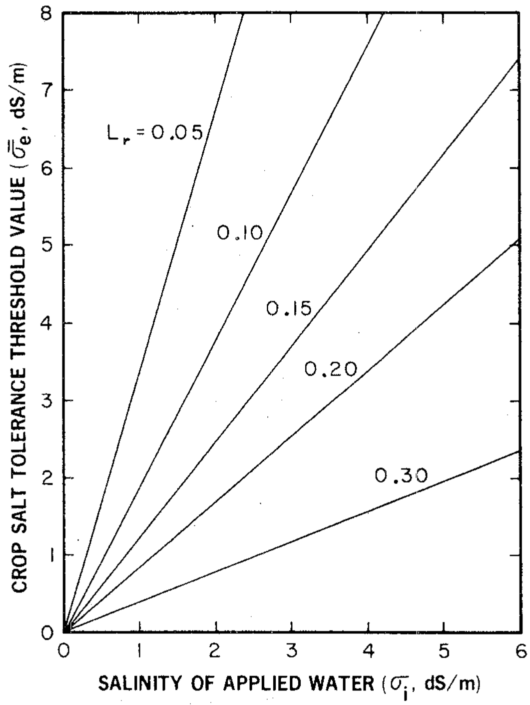

Fig. 6—Graphical solution for the leaching requirement (L_r) as a function of the salinity of the applied water and the salt-tolerance threshold value for the crop.

with L replaced by L_r. The resulting relationship, however, can not be applied directly, because the mean root-zone salinity for a given salinity of the applied water must be reduced if L is lower than L_r to prevent yield reduction or, conversely, L could be increased if the crop could tolerate more salinity. Unfortunately, no mathematical relationship has been developed to span this gap.

Plants adjust osmotically as soil salinity increases (Maas & Nieman, 1978). In salt-tolerance trials, this adjustment is sufficient to prevent yield loss until soil salinity surpasses the salt-tolerance threshold. Because salt-tolerance trials usually are designed to maintain leaching fractions approaching 0.5, the osmotic adjustment consistent with no yield loss can be estimated by the mean soil salinity at 50% leaching, as given in Fig. 5. As a first approximation, the leaching requirement can be expressed as a function of the threshold value by reducing $\overline{C_1}$ at any given L by $\overline{C_1}$ at 50% leaching. This relationship among salinity of the irrigation water, crop salt-tolerance threshold, and leaching requirement is illustrated in Fig. 6.

Comparisons among calculated leaching requirements and those measured experimentally are given in Table 1. Linear regressions correlating these calculated and measured values are given in Fig. 7 for each of the predictive models listed in Table 2. Predicting L_r by $\sigma_I/\sigma_{e_{50}}$ consistently overestimates, and by $\sigma_I/2\sigma_{e_0}$ consistently underestimates, the leaching require-

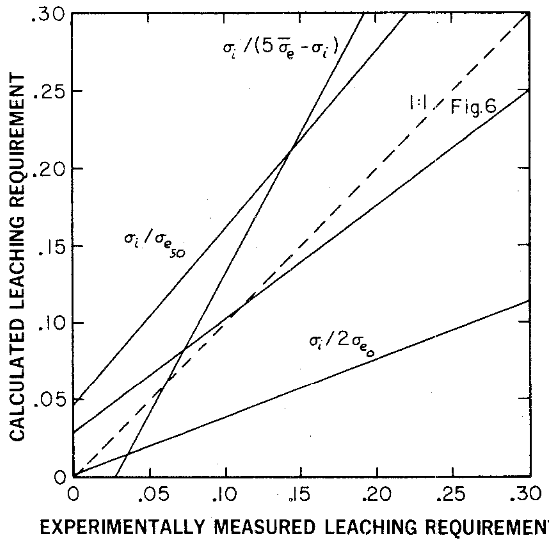

Fig. 7—Comparison of experimentally measured leaching requirements for six crops with empirically calculated leaching requirements. Data for establishing the least-squares linear regressions are taken from Table 1 for those experiments where a precise leaching requirement was reported.

ment. Predicting L_r from $\sigma_I/(5\sigma_t - \sigma_I)$ also overestimates the L_r, except at low L_r. Although not perfect, the L_r predictions from Fig. 6 agree well with the measured values throughout the range of L_r's of agricultural interest. In view of our ability to measure the leaching fraction in the field, Fig. 6 is a suitable estimate of leaching requirement.

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